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The center has participated actively with the graduate school of MIT, in a Minority Summer Research Program, to effect changes in the realm of graduate scientific training for minorities. It is also an active participant in the Research Scientist Institute (RSI) program with the Washington-based Center of Excellence in Education (CEE) in sponsoring the preparation of genius-level high school students recruited worldwide in preparation for them to achieve the ultimate of their capabilities. CEE was founded by Admiral Rickover in 1983 and its honorary trustees include such luminaries as former president Jimmy Carter, Senator Joseph Leiberman, and General Colin Powell. In addition, the MIT center has maintained an active visiting scientists program, which has kept our research program vibrant and up-to-date.

During the period, the members of the center have published 47 scientific papers, 7 books and proceedings, and have been invited to deliver 56 invited and review lectures at various international conferences and renowned educational and research institutions.

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I. ABSTRACT

The Center for Theoretical Geo/Cosmo Plasma Physics was established by the Air Force Office of Scientific Research in 1986 through a DoD University Research Initiative (URI) Grant via keen national competition. The goal of the center since its inception has been to develop and maintain a program of excellence in interdisciplinary space plasma research involving the mutual interactions of collaborating members of a select group of space scientists, plasma physicists, mathematicians and numerical analysts. During the past several years, under the new grant title, "Frontier Geoplasma Research", members of the center have made seminal contributions to a number of definitive research findings related to the phenomena of intermittent plasma turbulence, forced and/or self-organized criticality, global acceleration of the solar wind and polar wind, sporadic localized reconnections in the magnetotail and in the auroral zone, charged particle energization through wave-particle interactions, the black auroral curls, multi-scale evolutions, magnetosphere/ionosphere coupling, and the theory of complexity in space plasmas. Some of the results of these research activities have already found practical applications toward the missions of the United States Air Force, primarily through the collaborating efforts between the center members and members of the research group headed by Dr. J. R. Jasperse at the Air Force Research Laboratory.

The MIT Center is now recognized by their peers worldwide as a star example of a successful enterprise between a prestigious educational institution and an established governmental research laboratory, the Air Force Research Laboratory [AFRL]. In addition to our collaborating research efforts, our center and AFRL have co-sponsored a symposium series on the "Physics of Space Plasmas" and a workshop series on "Theoretical Geoplasma Physics", now under the combined name, the "Cambridge Symposia/Workshops on Space Plasma Research". The center also periodically co-

sponsors other scientific workshops and symposia with other institutions on various important topics of current space plasma research. Proceedings of these symposia and workshops have become important research resources for these current topics. For example, one such recent volume was devoted to the memory of Professor Subrahmanyan Chandrasekhar, a Nobel laureate and a giant in the scientific fields of plasma physics, astrophysics and space sciences. Another noteworthy contribution is the volume of a collection of outstanding contributions in the modern physics of complexity to be published as a special issue entitled "Forced and/or Self-Organiced Criticality [FSOC] in Space Plasmas" by the Journal of Atmospheric and Solar-Terrestrial Physics [JASTP].

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II. INTRODUCTION

For the United States Air Force to enjoy its continuing success in meeting the demands of its mission heading into the 21st century, it must be prepared to operate in the "New Frontiers" of space, particularly its ever-changing turbulent geoplasma environment. Recognizing this importance, a Center of Excellence in Theoretical Geo/Cosmo Plasma Physics was established (through keen national competition) at the Massachusetts Institute of Technology under the sponsorship of the Air Force Office of Scientific Research.

Benefiting from strong interactions with the members of the Air Force Research Laboratory at Hanscom, MA, our Center has made substantive progress toward the goals set forth since its inception. The close proximity between the two institutions has allowed direct personnel exchanges as well as direct and meaningful collaborations in numerous relevant research programs in geoplasma physics. During the past few years, under the new grant name, "Frontier Geoplasma Research", we have succeeded in jointly developing the fundamental understanding of several multiscale space plasma phenomena of cutting-edge importance. These include the study of the origin of broad-band low frequency turbulence in the auroral zone and the associated wave-particle interactions such as the anomalous acceleration of ionospheric oxygen ions into magnetospheric energies, the global acceleration and evolution of fast solar streams into the distant heliosphere, the generation of intense divergent electric fields and the phenomena of black auroral curls, the self-consistent kinetic evolution and the dynamic understanding of the day-night asymmetry of photoelectron-driven polar winds, the onset of coherent structures and associated double layers in the acceleration region of the ionosphere, the study of intermittent turbulence and sporadic localized reconnections in the Earth's magnetotail, the formation of ion conics and counter-streaming electrons along auroral field lines, and the general phenomena involving

the coupling of the ionosphere, magnetosphere, and the solar wind. Together, we have published (during the past several years) 47 joint technical papers and 7 books, and delivered 56 invited and review lectures at various international conferences and renowned institutions.

A number of the afore-mentioned research findings have already found practical applications by our colleagues at the Air Force Research Laboratory. Examples of such applications are: the prediction of charged-particle precipitation patterns and deposition profiles in the diffuse-auroral zone of the ionosphere, the prediction of solar EUV and X-ray fluxes based on the ionospheric photoelectron measurements and transport calculations, and the calculation of ionospheric electron density profiles in the equatorial, mid- and high-latitude portions of the globe and associated local, nonlocal, and nonlinear instabilities.

Our Center and the Air Force Research Laboratory (led by Drs. Tom Chang at MIT and J. R. Jasperse at AFRL) jointly inaugurated a series of symposia on the "Physics of Space Plasmas". The original purpose of these symposia is to provide an annual get-together for space scientists in the Boston-New England area. Its coverage has since attracted contributions from scientists worldwide. Each symposium included the presentation of an "Alfvén lecture" established in honor of the Nobel Laureate, Professor Hannes Alfvén of the Swedish Royal Institute of Technology. Professor Alfvén has strongly supported the activities of the MIT center. He was a founding honorary member of the center and visited the center often during its formative years. Alfvén Lecturers have included such luminaries as Professor Oscar Buneman of the Stanford University, Professor Jim Dungey of the Imperial College, London, Professor Eugene Parker of the University of Chicago, Dr. Roger Gendrin of the French National Laboratory of Ionospheric and Magnetospheric Physics, Professor James van Allen of the University of Iowa, Professor Charles Kennel of UCLA and the Scripps Institution

(and a former Associate Administrator of NASA), and Professor Alfvén himself who inaugurated the series.

Jointly with AFRL, we also organized a series of workshops in "Geoplasma Research". Each workshop was targeted at a specific topic of frontier geoplasma physics and includes basic tutorial talks and invited specialty lectures. The format of the workshops has been designed to allow ample discussion time and individual interactions. Since the untimely passing of Professor Alfvén, we have combined the symposium-workshop activities into a single series entitled: the "Cambridge Symposia/Workshops on Space Plasma Physics". During our recent 15th Cambridge Symposium/Workshop held in Cascais, Portugal, Professor Carl-Gunne Fälthammar of the Royal Institute of Technology and the Alfvén Laboratory of Plasma Physics, a favorite student of Professor Alfvén, was the first Alfvén Memorial Lecturer of the new series. Such activities have received much praise from the worldwide geo/cosmo community. Proceedings of the series entitled, "Physics of Space Plasmas", have become informal textbooks treasured by both established scientists and students in geo/cosmo research. The center also periodically co-sponsors other scientific workshops and symposia with other institutions on various important topics of current space plasma research. One such recent volume was devoted to the memory of Professor Subrahmanyan Chandrasekhar. Professor Chandrasekhar, a Nobel laureate, was a giant in the scientific fields of plasma physics, statistical mechanics, astrophysics and space sciences, radiative transfer, and MHD stability. This memorial volume covers the entire spectrum of "Chandra's" research interests. Another noteworthy contribution by the center is the editing of the collection of a set of outstanding contributions by a group of international scientists whose specialty are in the physics of complexity in a special issue entitled "Forced and/or Self-Organiced Criticality [FSOC] in Space Plasmas" to be published by the Journal of Atmospheric and Solar-Terrestrial Physics

[JASTP].

Onr center has interacted actively with a number or research organizations and universities in addition to the Air Force Research Laboratory. These include, the International Space Science Institute in Bern, Switzerland, the Italian National Space Research Institute in Rome, the Institute of Space and Astronautical Science, Japan, the University of Calgary, Canada, the Applied Physics Laboratory of the Johns Hopkins University, the Max-Planck Institutes for Extraterrestrial Physics and Aeronomy in Germany, the Lockheed-Martin Palo Alto Research Laboratory, the Universities of California at Berkeley, Los Angeles and Irvine, the Cornell University, the University of New Hampshire, NASA Goddard Space Flight Center, the National Research Council of Canada, the Naval Research Laboratory, the Imperial College of London, the University of Warwick, England, the British Antarctic Survey, Boston College, the Boston University, the Umeå University and the Uppsala University of Sweden. Visits to these institutions and by scientists from these institutions have provided the necessary stimulus to keep our research program vibrant, up-to-date, and at the same time constantly in touch with practical applications.

One of the prime missions of the MIT Center for Theoretical Geo/Cosmo Plasma Physics is to provide an environment for the development of young prospective students in space plasma education. During the past several years, in cooperation with the MIT Graduate School and the MIT Minority Summer Research Program (MSRP), our center hosted a number of talented young minority and female undergraduate interns. By intermingling with the established scientists at the center, these young interns obtained first hand knowledge of the true meaning of cutting-edge scientific research in space physics. The MIT Center also played an active role in the Research Scientist Institute (RSI) program in collaboration with the Washington-based Center of Excellence in Education (CEE) in sponsoring the education of genius-level high

school students recruited worldwide in preparation for them to achieve the ultimate of their scientific capabilities. CEE was founded by Admiral Rickover in 1983 and its honorary trustees include such luminaries as former president Jimmy Carter, Senator Joseph Leiberman, and General Colin Powell. RSI alumni have dominated all scholarship competitions of national talent search programs and many have become leaders in the various fields of the 21st century cutting-edge scientific disciplines.

This report is organized as follows: In Sec. III, we discuss the progress of our center by including a complete list of the center research topics, followed by four subsections of detailed descriptions of our recent major accomplishments. In Section IV, we provide a selected list of scientific publications by members affiliated with the Center. A complete list of invited and review lectures by the center personnel given at various conferences, meetings, and research institutions is given in Section V. Finally, a list of the past and present center personnel along with the brief descriptions of their qualifications is given in Sec. VI.

III. PROGRESS AND ACCOMPLISHMENTS

In our original AFOSR URI proposal, we proposed a unique program of theoretical research in geoplasma physics. The Center would be a single cohesive unit of scientists from several disciplines interacting effectively with one another and with groups from external ongoing experimental research programs. It would not be the purpose of the Center to carry out routine data analyses. Instead, our approach would be to interact with the experimental groups and to identify from the analyzed data those problems that had no ready-made explanations and to focus our efforts on the solution of such new problems. At all times, we would not lose sight of the practical applications of the developed theories to the prime mission of the Air Force. During the past few years under the current grant program "Frontier Geoplasma Research", we have endeavored to follow such guidelines while developing the various research efforts at the Center. We identified many new, interesting, and at the same time puzzling geoplasma problems that were not admissible to "routine" solutions. We have provided theoretical understanding to a number of such identified problems. In many of these instances, we were able to provide quantitative descriptions of the phenomena or make useful theoretical predictions for future observations and applications.

The most exciting research findings of our group during this period included the development of a first truly kinetic theory of the global evolution of the fast stream solar wind including the wave-particle energization of the ions and electrons, an "Intermittent Turbulence Theory" of sporadic localized magnetic reconnections that is germane to the coupling process between the ionosphere and magnetosphere in the auroral region and in the dynamics of the plasma sheet of the Earth's magnetotail, the anomalous energization of ionospheric ions in the acceleration and reverse-current regions of the auroral zone, and the development of a novel theory of the photoelectron-driven polar wind based on the kinetic and anomalous heat transport

of the field-aligned electrons, and nonthermal ions in the dayside polar ionosphere. We have included below four sub-sections to describe the details and seminal aspects of these research results. Other important research activities of the center included: the study of the dynamics of the coherent structures such as double layers and fast electron holes in the ionosphere, the dynamics of upward propagating lightning strokes, the multi-dimensional aspects of the black auroral curls, the development and propagation of electromagnetic ion cyclotron waves throughout the terrestrial ionosphere, and various processes related to the coupling of the ionosphere and magnetosphere. A number of our research findings have recently been confirmed by the experimental data collected by high-time resolution instruments on board the FREJA, VIKING, POLAR, DE, FAST and "AKEBONO" satellites as well as the TOPAZ, SCIFER, AMICIST, and other high-altitude rockets. As it has been the history of all past research activities of the MIT Center, our recent work is directly related to AF C3I systems. The coupling phenomenon between the Earth's ionosphere and magnetosphere, intermittent MHD turbulence, the polar wind outflow, the black auroral curls, and ionospheric lower hybrid cavitary structures all have profound effects on the high-latitude electron and ion density profiles as well as signal and wave propagations. The understanding of these phenomena is germane to space surveillance, space launch and orbit operations, as well as space weather modeling and forecasting. In particular, our understanding of pitch-angle scattering and the dynamics of the central plasma sheet allowed us to construct a quantitative model of electron precipitation in the diffuse aurora. Because this precipitation helps control the electron density profile in the high-latitude ionosphere, it has a strong impact on the Air Force communication and surveillance systems that must operate in the region. Similarly, because of the effect of scintillation on these systems and the close relationship between scintillations and the high-latitude ionospheric turbulence, our quantitative models of the latter

phenomena and its consequences can be expected to have great utility in the practical business of ionospheric weather prediction.

Listed below are research topics that have been studied and analyzed by the members of the center personnel during the grant period followed by the four subsections on the solar wind, self-organized criticality, ion acceleration, and the polar wind.

- Sporadic, localized magnetic reconnection and intermittent turbulence in the ionosphere-magnetosphere coupling region and in the Earth's magnetotail.
- Anisotropic, kinetic polar wind driven by the dayside-photoelectrons.
- Ion heating by low frequency waves in Earth's ionosphere and magnetosphere.
- Kinetic theory of the global evolution of the fast stream solar wind including the wave-particle energization of the ions and electrons.
- Lower hybrid collapse, caviton turbulence, and charged particle energization in the topside ionosphere.
- Mode conversion processes involving the plasma turbulence of oxygen-hydrogen plasmas in the magnetosphere and ionosphere.
- Nonlinear vortex description of black auroral curls.
- Turbulent relaxation of magnetic fields in space plasmas.
- Path integral approach to nonlinear particle acceleration and diffusion in ionospheric plasmas.
- Ion and electron acceleration along auroral field lines.
- Nonlocal effects of finite beam-driven instabilities in space plasmas.
- Convection of ion cyclotron waves to ion heating regions.
- Broad-band spectrum of auroral plasma turbulence.
- Renormalization-group calculation of self-organized criticality and low-dimensional behavior of auroral substorm onsets.
- Theory of nonlinear electric fields in the auroral acceleration region.
- Stochastic MHD models for space plasmas.
- Multiple-cyclotron absorption of ion heating in the cusp/cleft region.

- Wave-particle ion cyclotron turbulence and evolution of the electron distribution in inhomogeneous space plasmas.
- ULF waves along auroral field lines in the central plasma sheet.
- Energy source and generation mechanism for auroral kilometric radiation.
- Upward propagating intense lightning strokes and associated infrared emissions in the lower ionosphere.
- Particle acceleration by intense auroral VLF waves.
- The electron beam instability and turbulence theories in space plasmas.
- Two stream interaction on auroral field lines.
- Energetic photoelectron and the polar rain.
- Monte-Carlo modeling of polar wind electron distributions with anomalous heat flux.
- Counterstreaming electrons generated by lower hybrid waves in the auroral region.
- Heating of thermal ions near the equatorward boundary of the mid-altitude polar cusp.
- Stabilization of the cyclotron autoresonance maser instability in space plasmas.
- Nonlinear oblique whistler modes in collisionless shocks of space plasmas.
- Electromagnetic tornadoes in space.
- Radiations from large space structures in low Earth orbit with induced AC currents.
- Ion waves and upgoing ion beams observed by the VIKING satellite.
- Simulation of ion conic formation in the ionosphere and magnetosphere.
- Alfvén engine in space.
- Convection of ion cyclotron waves to ion heating regions in the auroral zone.
- Wave observations and their relation to nonresonant and resonant particle heating processes.

III.1 Effect of Electron Resonant Heating on the Kinetic Evolution and Acceleration of the Solar Wind

Abstract

We investigate the effects of electron cyclotron resonant heating on the kinetic evolution and acceleration of the fast solar wind. A previous study based on a global hybrid model has shown that kinetic wave-particle interactions, in particular, those due to ion resonant heating, may account for the bulk acceleration of the solar wind, the preferential heating of the helium ions over the protons, as well as the occasionally observed double-peaked proton velocity distributions. The model followed the evolution of the particle distributions along an inhomogeneous field line under the effect of ion heating, an ambipolar electric field that is consistent with the particle distributions themselves, and Coulomb collisions. This study extends the model to take into account also the effect of electron cyclotron resonant heating. Our parametric study shows that the electron heating does not change the solar wind qualitative features described above. However, the wave-particle interaction increases the ambipolar electric field, thereby enhancing the solar wind velocity.

III.1.1 Introduction

The role of ion resonant heating in the global kinetic evolution of the solar wind has recently been investigated by *Tam and Chang* [1999] (TC99). The study followed the kinetic evolution of the solar wind particle distributions from 1 $R_\odot$ (solar radius) to 1 AU, while taking into account the effects of ion cyclotron resonant heating, Coulomb collisions, and an ambipolar electric field that was consistent with the particle distributions themselves. The results of the study addressed some qualitative features observed in the fast solar wind. For example, the preferential heating of the helium ions over the protons due to wave-particle interactions translates into a higher

velocity downstream in the solar wind. That provides an explanation for the helium to be the faster major ion species in the solar wind, as observed, for example, by the Helios, WIND, and Ulysses spacecraft [*Marsch et al.*, 1982a; *Steinberg et al.*, 1996; *Feldman et al.*, 1996]. Moreover, the results of TC99 featured double peaks in the proton velocity distributions, which were occasionally observed by the Helios spacecraft [*Marsch et al.*, 1982b]. The formation of the double-peaked proton distributions in the theoretical study was explained as a result of the combined effects due to resonant heating in the corona by the inward propagating component of the left-hand polarized waves, and the mirror folding of the velocity distributions downstream in the solar wind.

While our previous work showed that wave-particle interactions play an important role in the acceleration of the solar wind, we considered only the cyclotron resonances involving the major ion species (proton and helium) in the solar wind. This study concentrates on another type of kinetic wave-particle interactions that may have a significant effect on the solar wind, namely electron cyclotron resonances. Note that for plasma outflows in space, such as the solar wind, electrons may significantly affect the overall dynamics through their heat flux contributions. It has been shown that in the ionospheric polar wind, which is another example of outflow in space plasmas, the electron heat flux is mainly carried by the photoelectrons, rather than by the thermal population. The presence of photoelectrons, due to their heat flux contribution, significantly enhances the self-consistent ambipolar electric field, leading to higher outflow velocities of the ions [*Tam et al.*, 1995, 1998]. In the solar wind, wave-particle interactions may anisotropize the electron population, generating non-thermal features in their distributions and thereby enhancing the suprathermal electron components. Due to its effect on the electron heat flux, electron cyclotron resonant heating may modify the ambipolar electric field considerably, and in turn,

significantly affect the kinetic evolution and acceleration of the solar wind.

In Section III.1.2, we shall discuss how we modify our previous solar wind model to take into account two new physical effects: first, electron cyclotron resonant heating as discussed above; second, heating in the direction parallel to the magnetic field. Note that in our previous study, the ions were heated only in the transverse direction, whereas in this study, all the particle species (both ions and electrons) are heated in the parallel and perpendicular directions. In Section III.1.3, we shall discuss results of a parametric study, from which one can understand the effects of electron cyclotron resonant heating on the kinetic evolution of the solar wind. A summary of these effects will given in Section III.1.4.

III.1.2 Model

As mentioned above, this study is an extension of the work by TC99. We shall briefly review the previous model, and discuss how it is modified to incorporate the new physical effects that we are interested in.

The ion resonant heating in the previous study involves low frequency electromagnetic waves whose wavevector component $k_\perp \ll k_\parallel \approx k$. Because we also consider electron cyclotron resonant heating here, the frequency of the waves that we are interested in extends to the electron cyclotron frequency range. The resonant conditions for the ions are the same as in TC99, while those for the electrons are similarly defined. Specifically, a particle with parallel velocity $v'_\parallel$ in the solar wind frame resonates with the right-hand polarized (RHP) components of the waves when the following conditions are satisfied:

$$\omega' - kv'_\parallel + \Omega = 0 \ , \tag{III.1.1}$$

where ω' is the wave frequency in the solar wind frame, and Ω is the cyclotron frequency of the particle, defined to be positive for the ions, and negative for the elec-

trons. For resonances involving the left-hand polarized (LHP) waves, the condition is:

$$\omega' - kv'_{\|} - \Omega = 0 \ , \tag{III.1.2}$$

Equation (III.1.1), combined with the cold plasma dispersion relation, determines the resonant frequencies and wave-vectors for individual ions and electrons. However, in this study we consider electron resonances with only the RHP waves. Thus, Eq. (III.1.2) is applied only for the ions.

The effect of these wave-particle interactions is incorporated into the steady-state collisional kinetic equation for the solar wind ions:

$$\left[v_{\|}\frac{\partial}{\partial s} - \left(g - \frac{q}{m}E_{\|}\right)\frac{\partial}{\partial v_{\|}} - {v_{\perp}}^2\frac{B'}{2B}\left(\frac{\partial}{\partial v_{\|}} - \frac{v_{\|}}{v_{\perp}}\frac{\partial}{\partial v_{\perp}}\right)\right] f_j = C_j f_j + D_j f_j, \tag{III.1.3}$$

where $v_{\|}$ and $v_{\perp}$ denote velocities in the spacecraft frame, $f_j(s, v_{\|}, v_{\perp})$ is the distribution function for the species j, s is the distance along the magnetic field line, B is the magnetic field, q and m are the algebraic electric charge and mass of the species respectively, $E_{\|}$ is the field-aligned ambipolar electric field, g is the gravitational acceleration, $B' \equiv dB/ds$, C_j is a Coulomb collisional operator for the species j, and

$$D_j = \frac{\partial}{\partial v_{\|}} D_{j\|} \frac{\partial}{\partial v_{\|}} + \frac{1}{v_{\perp}}\frac{\partial}{\partial v_{\perp}}\left(v_{\perp} D_{j\perp}\frac{\partial}{\partial v_{\perp}}\right) \tag{III.1.4}$$

is an operator that describes the resonant heating, with $D_{j\|}$ and $D_{j\perp}$ being diffusion coefficients that represent heating in the parallel and perpendicular directions respectively. The diffusion coefficients may consist of contributions from LHP and RHP waves, and can be expressed as a sum of the two:

$$D_{j\|} = \eta_L D^L_{j\|} + \eta_R D^R_{j\|} \ , \quad \text{and} \tag{III.1.5}$$

$$D_{j\perp} = \eta_L D^L_{j\perp} + \eta_R D^R_{j\perp} \ , \tag{III.1.6}$$

where the subscripts in the notation $D^{L,R}_{j\|,\perp}$ denote the species and the direction of the resonant heating the diffusion coefficient emphasizes, and the superscript indicates the

the polarization of the waves resonating with the particles under condition (III.1.1) or (III.1.2). The parameters $\eta_{L,R}$ are factors that adjust the efficiency of the heating. The reasons for these adjustments have been discussed by TC99, one of those being consistent with a recent study of wave dissipation near the corona [*Cranmer et al.*, 1999].

We use a model similar to that in TC99 to describe the effects included in Eq. (III.1.3) to (III.1.6). The model enables us not only to follow the global evolution of the solar wind particle distributions under the effect of wave-particle interactions and Coulomb collisions, but also to determine the influence of the ambipolar electric field that is consistent with the distributions themselves. It utilizes two techniques that had existed in the literature: the self-consistent hybrid model applied to the ionospheric polar wind [*Tam et al.*, 1995] and Monte Carlo modeling of ion resonant heating [*Retterer et al.*, 1983]. The self-consistent hybrid model has been described in detail by *Tam et al.* [1998]. In the model, the global evolution of the ion distributions is based on kinetic calculations that, among other major effects, also take into account the Coulomb interactions, including those among the same ion species. The suprathermal electrons, which are the tail portion of the thermal electron distribution at the lower boundary, are also described by a similar approach, except that they are treated as test particles due to their low relative density. The bulk thermal electrons, assumed to be in the form of a drifting Maxwellian, and the ambipolar field are determined with a fluid approach. In this study, we extend the Monte Carlo modeling technique [*Retterer et al.*, 1983] also to the electron population, and take into account the global kinetic effect of electron cyclotron resonant heating.

However, we found that resonant heating is not always the dominant effect governing the evolution of the electron population. Near the corona, the Coulomb collisional effect is very strong because of the high electron density. This collisional effect is

velocity-dependent [*Scudder and Olbert*, 1979]; it is stronger in the core, and weaker in the tail of the electron distributions. Thus, there is a regime in the electron distributions dominated by Coulomb collisions, whose effect tends to hold the electron core together in the solar wind flow. We have compared the Coulomb collisional effect with that due to electron resonant heating, and estimated that the following criterion applies to the regime not dominated by Coulomb collisions: $m_e v'^2/2 \geq 5T_e$ at $1R_\odot$, where T_e is the electron temperature. All the individual electrons that satisfy this criterion are treated as "suprathermal" electrons with the kinetic approach described above. The rest of the electron population is considered thermal electrons.

III.1.3 Parametric Study

Using the assumptions in our previous work on the interplanetary magnetic field [*Banaszkiewicz et al.*, 1998], the wave power spectrum [*Bavassano et al.*, 1982], and the ratio between the inward and outward propagating wave power, we have performed a parametric study that would indicate the effect of electron cyclotron resonant heating on the kinetic evolution of the solar wind. Specifically, we investigate how the solar wind changes with different values of the parameter η_R. As in our previous work, η_L is assumed to be:

$$\eta_L = 1.25 \times 10^{-2} \exp\left(\frac{1-r}{0.5}\right), \tag{III.1.7}$$

where r is heliocentric distance in the unit of $R_\odot$. Here, we shall present results of the solar wind for three different cases: (a) $\eta_R = 0$; (b) $\eta_R = 0.1\,\eta_L$; (c) $\eta_R = \eta_L$. Note that electron cyclotron resonant heating increases from (a) to (c). Except for η_R, all the other parameters and boundary conditions in the three cases are the same. At the lower boundary, the proton and helium densities are respectively 1.5×10^7 and 2×10^6 cm^{-3}, and the electron temperature is 2×10^6 K.

One effect of electron cyclotron resonant heating, as expected, is the enhancement

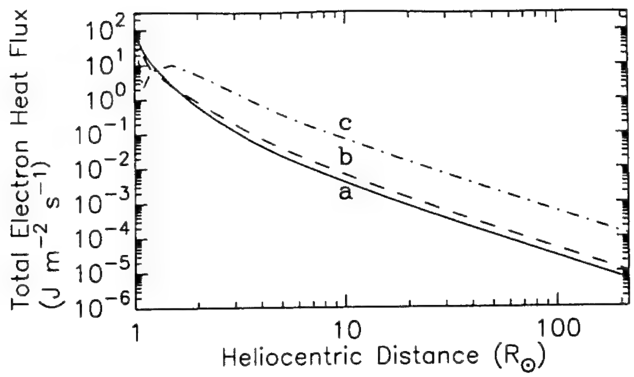

Figure III.1.1: Total electron heat flux profiles for the three solar wind cases (labeled a, b, and c).

of the electron temperature. The resonant heating also affects the total electron heat flux. Figure III.1.1 shows that the total electron heat flux increases from (a) to (c) as a result of the resonant heating. The electron heat flux profiles follow closely to a power law from a few solar radii to 1 AU. Their power-law indices range from -2.03 to -2.06, in agreement with the estimates based on a number of high-speed solar wind events observed by the Helios spacecraft [*Pilipp et al.*, 1990]. As discussed by *Tam et al.* [1998] in their ionospheric polar wind study, the increase in the overall electron flux may enhance the self-consistent ambipolar electric field. Figure III.1.2 shows the ambipolar electric potential profiles for the three solar wind cases. The potential drop from the sun to 1 AU increases significantly from Cases (a) to (c). Hence, the ambipolar electric field increases as a result of electron cyclotron resonant heating. The reason of this increase, as in the ionospheric polar wind, is due to the enhancement of the total electron heat flux by resonant heating.

Due to the increase in the ambipolar electric field, the proton velocity u_p also significantly increases from Cases (a) to (c), as shown in Fig. III.1.3. The same is also true for the helium ion velocity u_α. Therefore, electron cyclotron resonant heating can be considered as an acceleration mechanism of the solar wind, although its contribution in accelerating the ions seems less than those by ion resonances.

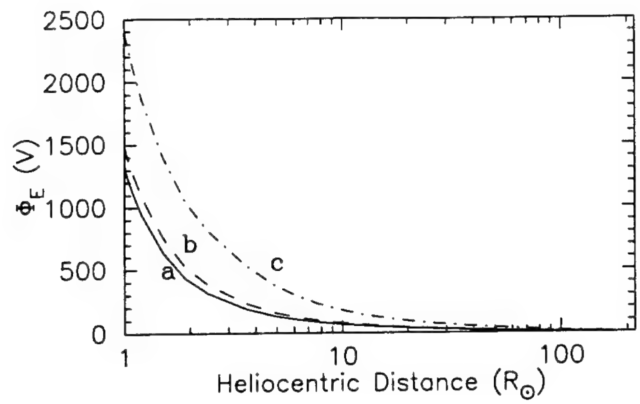

Figure III.1.2: Profiles of the ambipolar electric potential for the three solar wind cases.

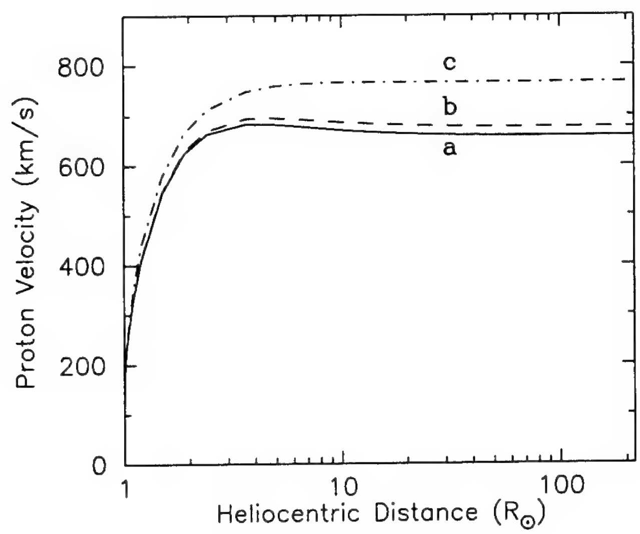

Figure III.1.3: Solar wind proton velocities for the three cases.

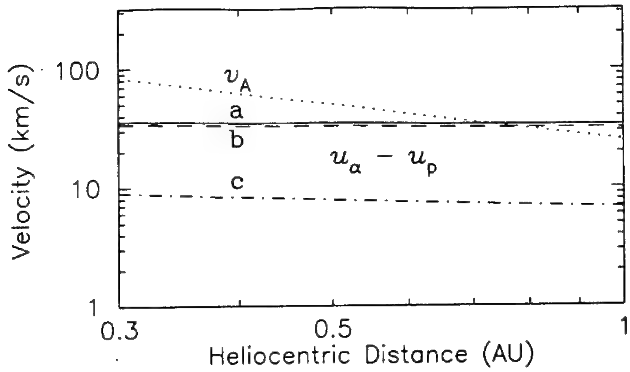

Figure III.1.4: Ion differential velocity, $u_\alpha - u_p$, for the three cases. The local Alfvén speed v_A is included for reference.

Because electron resonant heating accelerates the ions mainly by means of its effect on the ambipolar electric field, we expect the protons rather than the helium ions to gain more speed because of their higher charge-to-mass ratio. Indeed, when we compare the ion velocities of the three solar wind cases, we find that the ion differential speed, $u_\alpha - u_p$, is smaller as the amount of electron resonant heating increases, as shown in Fig. III.1.4.

Figure III.1.5 shows the parallel temperatures of the ion species in our results. Case (c) has significantly lower ion temperatures than the other two cases. The reason is due to the global kinetic effect of the solar wind flow. Note that because of a higher ambipolar electric field, the ions are traveling faster in Case (c). That reduces their resident time near the corona, where the majority of ion resonant heating occurs. Thus, the amount of resonant heating received by the ions is smaller in (c). Due to the global kinetic nature of the solar wind flow, the ion temperatures downstream in that case are also smaller. These ion temperatures, nevertheless, are still about 2 times higher than the corresponding observed values. As suggested by TC99, the lower observed values may be due to resonant heating below 1 $R_\odot$, which the present study does not take into account. We should note that like the ion temperatures shown in Fig. 2 of TC99, the temperatures in Fig. III.1.5 reflect only the effect of resonant

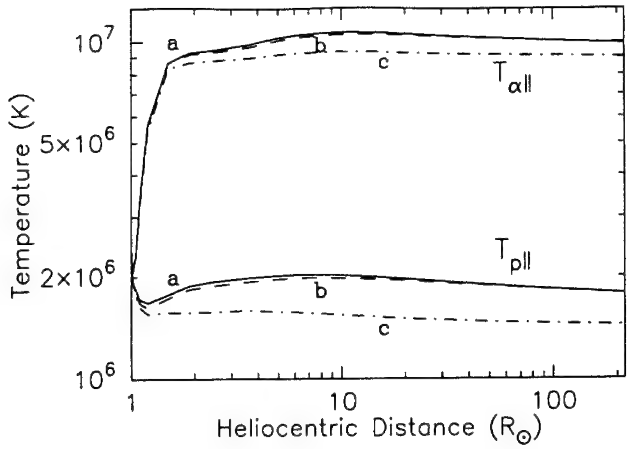

Figure III.1.5: Profiles of parallel temperatures for the protons (subscript p), and the helium ions (subscript α) in the three solar wind cases (labeled a, b, and c).

heating near the corona. We have not taken into account the modification due to local resonant heating downstream in the solar wind. Under this approximation, the ion perpendicular temperatures in the two studies are of the same order. We have shown in our previous study that inclusion of local resonant heating does not change the ion parallel temperature or the ion velocities by a significant extent, but can render ion distributions consistent with Helios observations [*Marsch et al.*, 1982b].

By comparing the results of the three solar wind cases from the figures, one can conclude that the presence of electron cyclotron resonant heating, despite its significant modification on the solar wind quantities such as the ion temperatures, does not change the qualitative behavior of the outflow. Among other qualitative features in the solar wind, the double-peaked proton velocity distributions exist in all three cases.

III.1.4 Conclusion

We have investigated the effects of electron cyclotron resonant heating on the global kinetic evolution of the solar wind. Our model describes the kinetic evolution

of the solar wind particle distributions under the effects of wave-particle interactions, Coulomb collisions, and an ambipolar electric field that is consistent with the particle distributions themselves. The results based on our parametric study show that electron resonant heating increases the electron temperature and heat flux, leading to a larger ambipolar electric field in the solar wind. The effect of electron resonant heating on the ions are mainly through the ambipolar field. Electron heating leads to higher ion velocities with the protons being preferentially accelerated. That results in a decrease in the ion differential speed in the solar wind. Ion temperatures are also lower in the presence of electron heating.

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III.2 Self-Organized Criticality, Multi-Fractal Spectra, and Intermittent Merging of Coherent Structures in the Magnetotail

Abstract

In 1992, Chang suggested that substorm dynamics of the Earth's magnetotail may be described by the stochastic behavior of a nonlinear dynamical system near forced or self-organized criticality (SOC). Subsequently, *Chang* [1997, 1998] demonstrated that multiscale intermittent turbulence of overlapping shear Alfvén and other plasma resonances is the underlying physics that can lead to the onset and evolution of substorms. Such a description provides a convenient explanation of the localized and sporadic nature of the bursty bulk flows that are commonly observed in the magnetotail [*Angelopoulos et al.*, 1996; *Lui*, 1998]. These concepts lead to a new paradim for the understanding of the ever-elusive phenomenon of substorms. In this report, we describe some of the basic physical concepts that play an important role in the development of these new ideas.

III.2.1 Descriptive Outline

The organization of this section of the report is as follows. In Section III.2.2, we provide the framework for a multiscale intermittent turbulence model of sporadic localized merging for the magnetotail. We will demonstrate that such a dynamic process will generally require the existence of an underlying three-dimensional magnetic field geometry, and that coherent flux structures and localized merging can set in near sites of shear Alfvén resonances.

In Section III.2.3, we digress and discuss the implications of the individualized merging of coherent structures. We suggest that these are the localized reconnection signatures observed by spacecraft flying through the neutral sheet region of the magnetotail and that they are the origins of the observed *bursty bulk flows.*

In Section III.2.4, it is suggested that the onset of substorms is due to the appearance of a global, nonclassical, nonlinear instability signaled by the enhanced mixing and merging of the coherent structures and plasma fluctuations. The ensuing substorm dynamics is then suggested to be characterized by the phenomenon of self-organized criticality (SOC).

For nonlinear stochastic systems near forced or self-organized criticality, the correlations among the fluctuations of the random dynamic fields are extremely long-ranged and there exist many correlation scales. Using the techniques of the theory of the renormalization-group [*Chang et al.*, 1992], it was demonstrated by *Chang* [1992] that such dynamical systems will acquire the apparent characteristics of low-dimensionality and fractal structures; thus, providing a rationale for the recent low-dimensional studies for substorm dynamics [*Baker et al.*, 1990; *Klimas et al.*, 1992, 1998; *Sharma et al.*, 1993].

In Section III.2.5, we discuss the importance of the fluctuation spectra for the inhomogeneous anisotropic intermittent turbulent plasma medium of the magnetotail during substorms. The concept of multi-fractals is introduced and related to the scaling regions of the spectra for coherent, MHD and kinetic states. The concept of crossover and symmetry breaking will be introduced to interpret the dynamic spectra.

The section concludes, in Section III.2.6, with a summary and a discussion of the implications of the proposed multiscale, intermittent turbulence model of the magnetotail with suggestions for a number of tests of the theory both from the point-of-view of observations and numerical as well as laboratory simulations. A sufficiently complete set of references are provided for further reading and study.

III.2.2 Stochastic Merging of Coherent Structures

Measurements of reconnection signatures in the "neutral sheet" region of the

Earth's magnetotail indicate that most of the individual localized merging processes occur at intermediate or microscales. On the other hand, the dimensions of the full dynamic domain that is responsible for the transferring of energy and momentum from the solar wind to the Earth's magnetotail generally involve time and spatial scales much larger than those characterized by the microscopic plasma parameters such as the ion gyroradius, skin depth, Debye length, and ion cyclotron, lower hybrid or plasma frequencies. The transport processes at the two ends of the dynamic spectrum can involve characteristic parameters differ by orders of magnitude, suggesting that the underlying dynamics of the magnetotail is intrinsically multiscale.

Thus, we adopt a middle of the road approach in viewing the magnetotail by assuming that the dynamics of the plasma medium is primarily characterized by the basic MHD variables with an anisotropic pressure tensor. To bring in some of the possible kinetic effects, we can, e.g., relate the pressure tensor to the particle distribution functions $f_i(\mathbf{x}, \mathbf{v}, t)$ in terms of the appropriate moments. Standard arguments lead to the following set of coupled equations of induction and motion:

$$d\mathbf{B}/dt = (\mathbf{B} \cdot \nabla)\mathbf{V} + \ldots, \ \textit{and} \tag{III.2.1}$$

$$\rho \, d\mathbf{V}/dt = (\mathbf{B} \cdot \nabla)\mathbf{B} + \ldots, \tag{III.2.2}$$

where all notations are customary and the ellipsis represent compressibility, and anisotropic pressure effects. Generally, of course, dissipative terms must also be included. It is clear from above that one of the wave modes allowed by these equations is the shear Alfvén wave. For such modes to propagate, the propagation vector $\mathbf{k}$ must contain a field-aligned component, i.e., $\mathbf{B} \cdot \nabla \to i\mathbf{k} \cdot \mathbf{B} \neq 0$. However, at sites where the parallel component of the propagation vector vanishes, $k_{||} = \mathbf{k} \cdot \mathbf{B} = 0$, energies are localized and the field lines may be distorted effortlessly. These singularities (points, curves or surfaces) at which $k_{||} = 0$ are called "shear Alfvén resonances". As

it will be demonstrated below, the existence of shear Alfvén resonances will lead to the formation of nearly-nonpropagating and essentially closed macroscopic magnetic structures.

We now consider the magnetic field structures near the Alfvén resonances. Neglecting the pressure effects, it is clear from Eqs. (III.2.1), (III.2.2) that the forces arise from the fluctuations just away from these singular (resonance) sites, i.e., $\delta\mathbf{B}\cdot\nabla$, will tend to restore the field lines towards the resonance sites, thereby forming essentially closed coherent magnetic structures. In the following we shall consider the general topology of such coherent structures.

For an ideal MHD system, any physically acceptable magnetic field must satisfy $\nabla\cdot\mathbf{B} = 0$. Also, any variation of the field away from the initial value must satisfy the constraint:

$$\partial\mathbf{B}/\partial t = \nabla\times(\mathbf{v}\times\mathbf{B}). \tag{III.2.3}$$

Taylor [1974] demonstrated that Eq. (III.2.3) may be replaced by an infinite set of integral constraints involving the *helicity* K, such that

$$K = \int_V \mathbf{A}\cdot\mathbf{B}\,dV \tag{III.2.4}$$

is an invariant for any volume V enclosed by a flux surface, where $\mathbf{A}$ is the vector potential. It can be shown that as the system relaxes to its minimum energy state satisfying the helicity conservation constraints, the magnetic structure will be in a force-free state, i.e.,

$$\mathbf{j}\times\mathbf{B} = 0. \tag{III.2.5}$$

Coarse-Grained Helicity. Let us now consider our present situation at hand. We are interested in the more realistic situation that characterizes the dynamics of the magnetotail where the plasma is slightly dissipative and in addition, there are stochastic macroscopic (as well as microscopic) fluctuations. The dissipation and magnetic

stochasticity will allow the field lines to merge, mix, and break. It is obvious that it no longer makes sense to discuss the topology of individual field lines. Nevertheless, it was suggested by *Taylor* [1974] that when the volume integral for Eq. (III.2.4) is taken over the "stochastic region", the coarse-grain averaged helicity will be essentially conserved. This indicates that when considering the stochastic domain, the average magnetic structure in a relaxed state will again be essentially force free, with $\mathbf{j}\times\mathbf{B} = 0$, where $\mathbf{j}$ and $\mathbf{B}$ are now to be interpreted as the mean current and magnetic field, respectively. This result can also be arrived at using the clump theory of MHD turbulence [*Tetreault*, 1992, and references contained therein].

We are, of course, interested in the magnetotail at dynamic states that are far from equilibrium. Thus, in visualizing the relaxed states from the point of view of the Taylor's conjecture, we shall consider timescales such that "nearly coherent" magnetic structures are formed.

Let us now apply these concepts to the sheared magnetic field geometries that are generally found in the "neutral sheet" region of the magnetotail. The nearly force-free condition for the coarse-grain averaged coherent structures would then orient themselves more-or-less in the average cross-tail current direction in the form of twisted flux tubes. In general, there will be a constellation of such coherent structures immersed in the turbulent plasma medium, Fig. III.2.1.

III.2.3 Individual Localized Merging

As the coherent structures migrate toward each other, they will merge and form new coherent structures. Depending on the polarities and intensities of the currents that orient these flux tubes, the resulting coherent structures will be either larger or smaller than the original individual structures. The final states of the new coherent structures will again be essentially force-free in the coarse-grained sense. As these

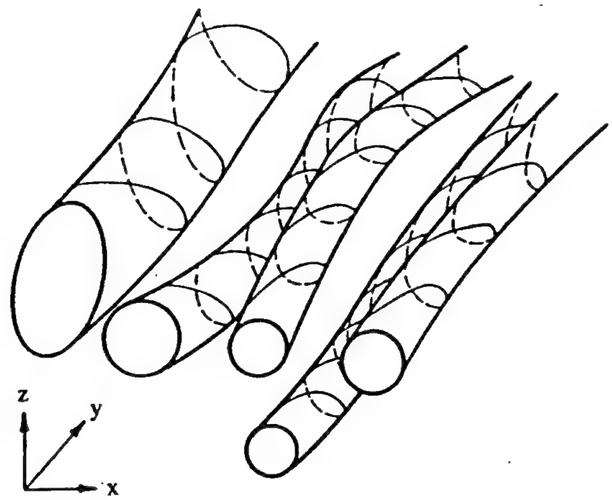

Figure III.2.1: Illustrative configuration of twisted flux tubes near the "neutral sheet."

new structures are generated, new MHD fluctuations are produced; and thereby spontaneously set up new resonance sites. Thus, an interesting scenario of intermittent turbulent mixing, diffusing, and merging sets in, Fig. III.2.2.

Let us consider the most probable situation of merging, i.e., the merging of two coherent structures. Viewed in a section normal to the average direction of the cross-tail current, the topologies of the field lines during such a merging process mimic that is generally considered for a classical magnetic "reconnection" process [Fig. III.2.3].

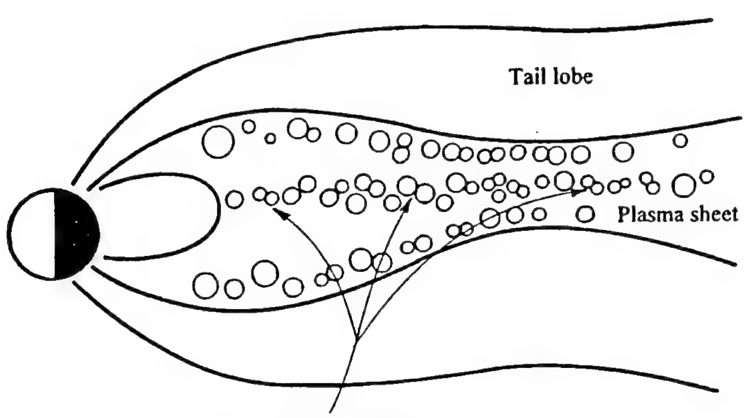

Figure III.2.2: Cross-sectional view of sporadically distributed flux tubes in the plasma sheet.

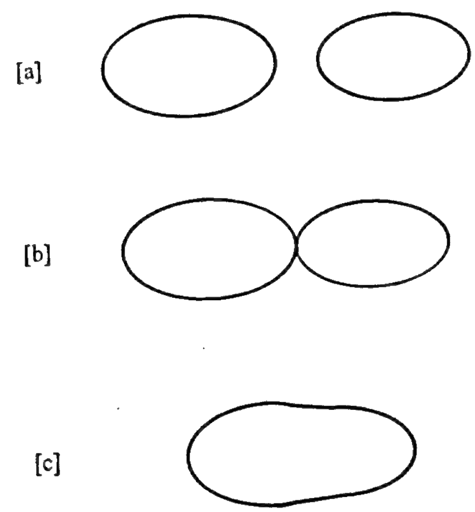

Figure III.2.3: Cross-sectional view of coherent structures at various stages of merging. (a) Just Prior to Merging. (b) During the process of merging. (c) Relaxed state after merging.

However, we note that this localized merging process can take place without the requirement of $\mathbf{B} = 0$ and/or the existence of a true "neutral line." In fact, as seen above, the prerequisite for the existence of many such coherent structures as well as the sporadic merging of these structures is the existence of many "Alfvén resonance" sites with $k_{\parallel} = 0$. This occurs when the background magnetic field is three-dimensional and nonzero and when there are three-dimensional macroscopic MHD fluctuations.

Thus, we suggest that as a spacecraft flies through the neutral sheet region of the magnetotail, there is a finite probability for the instruments on the spacecraft to detect classical-like reconnection signatures. Such signatures can be detected nearly anywhere in the plasma sheet, but more probably in the "neutral sheet" region, particularly during substorm times. The duration of interaction of these observed localized merging processes should be the approximate time required for the new relaxed coherent structures to emerge and in general, would be rather sporadic. We

suggest that these are the origins of the observed "bursty bulk flows" [*Angelopoulos et al.*, 1996; *Lui*, 1998; Kivelson and Kepko, private communication].

Most of the observed localized reconnection signatures to date seem to indicate that these localized merging processes take place in domain sizes comparable to that of the ion gyroradius, especially during substorm times. Thus, very probably most of these processes will be influenced by microscopic kinetic effects. During these dynamic processes, the ions can probably be assumed to be unmagnetized and the electrons fully magnetized and the plasma nearly collisionless. This, of course, would lead to electron-induced Hall currents. Depending on the underlying magnetic geometry (since these processes can occur at any arbitrary underlying magnetic field configuration), the relevant kinetic instability that can initiate the localized merging (or reconnection) can be any of the many recently suggested microscopic instabilities such as the collisionless tearing instability, cross-field two-stream instability [*Lui*, 1996], etc. It is very probable that the nonlinear state of merging for each of these localized reconnections again entails the phenomenon of overlapping resonances [*Galeev et al.*, 1986]. (Now these resonances will arise from the localization of microscopic fluctuations, e.g., the whistler resonances, and multiple tearing modes.)

III.2.4 Self-Organized Criticality and Low-Dimensional Behavior

Under favorable conditions (e.g., an enhancement of the cross-tail current due to the change of certain global controlling parameters for the magnetotail), the state of the turbulence discussed in the previous sections may grow (in terms of more plasma fluctuations and larger coherent structures).

This type of instability, by definition, is genuinely "nonlinear". For the onset and growth of a classical nonlinear instability, there generally exists a prescribed

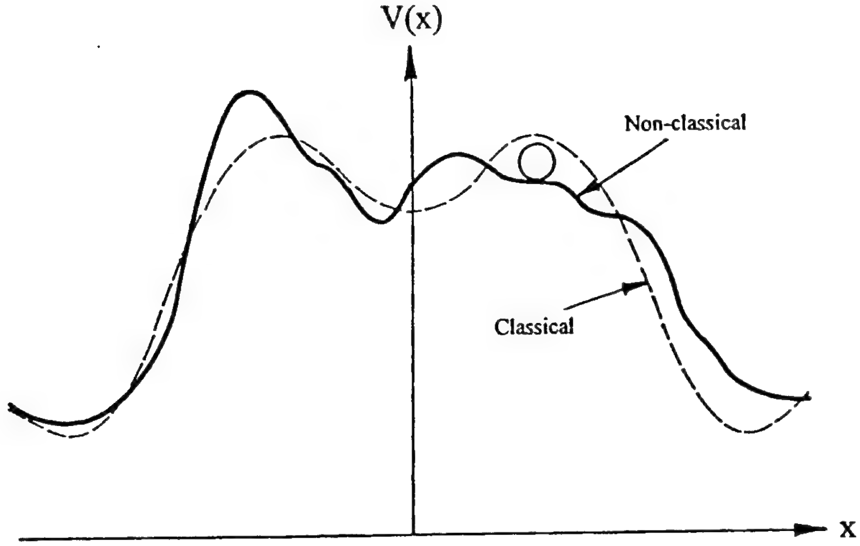

Figure III.2.4: Schematic depictions of classical and nonclassical, nonlinear instabilities.

minimum finite amplitude of disturbance (measured, for example, by the root-mean-square of fluctuations) beyond which the fluctuations and coherent structures can grow [Fig. III.2.4]. During the onset of a substorm, on the other hand, it has been recognized [*Chang*, 1992] that the non-equilibrium plasma state in the magnetotail is near criticality (similar to the critical point for equilibrium liquid/gas phase transitions.) At such a dynamic state (commonly referred to as a state of self-organized criticality, SOC), the effect of the fluctuations themselves becomes an important factor in determining the critical threshold of onset and the instability is now both "nonclassical" and "nonlinear". Such an instability is generally controlled by a set of relevant global parameters.

The dynamics of a system at self-organized criticality is notoriously difficult to handle because the correlations of the fluctuations are long-ranged and there exist many correlation scales. On the other hand, since the correlations are extremely long-ranged, it is reasonable to expect that the system will exhibit some sort of invariance under scale transformations [*Chang et al.*, 1992; *Chang*, 1992, 1998].

One of the most surprising results of such theoretical arguments (based on the ideas of the dynamic renormalization-group) is that, even though the magnetotail system is infinite-dimensional and entails many, many physical parameters, its dynamics near self-organized criticality (i.e., at the onset and during magnetic substorms) can actually be characterized by a small number of relevant physical parameters (low-dimensionality). Thus, the system can be approximately described by a small number of nonlinear equations that describe the evolution of these relevant physical parameters. In addition, near criticality, these low-dimensional nonlinear equations will generally exhibit chaotic (fractal) behavior.

In several recent interesting papers, [*Baker et al.*, 1990; *Klimas et al.*, 1991, 1992, 1998; *Baker*, 1998], it has been suggested that certain substorm characteristics in terms of the AL time series could be modeled by deterministic chaos of simple low-dimensional dynamic equations. These results suggest that the global magnetospheric system may be "very close" to forced or self-organized criticality.

Vassiliadis et al. [1990], *Shan et al.* [1991], and *Roberts et al.* [1991] applied the technique of *Grassberger and Procaccia* [1983] for finite dimensional systems to the AE/AL time series and estimated the dimensionally of the magnetospheric system during substorms. Their results seemed to indicate "fractals" and low-dimensional chaos.

Separately, *Sharma et al.* [1993] suggested that the dimensionality of the magnetospheric system might be obtained using the singular spectrum analysis constructed from the AE/AL time series. Their results also seemed to indicate low-dimensionality and chaos. These results appear to bestow credence to the hypothesis that substorm dynamics is indeed characterized by the phenomenon of self-organized criticality.

III.2.5 Symmetry Breaking and Multifractal Spectra

In previous sections, we demonstrated that the dynamics of the magnetotail is characterized by multiscale intermittent turbulence. A standard technique to study the behavior of such type of turbulence is through the properties of the spectra of the turbulent fluctuations.

For example, in the "neutral sheet" of the magnetotail, one of the more important spectra [Fig. III.2.5] to consider is that of the square of the magnetic fluctuations in the cross-tail direction $\langle \delta B^2 \rangle$. We expect the spectra to generally exhibit fractal characteristics (i.e., nonclassical slopes with discernible deviations from those obtainable by naive dimensional arguments). In regions where the fluctuations and merging dimensions are much larger than that of the local ion gyroradius, the spectrum is expected to exhibit two distinguishable parts: a domain characterized by the larger scale coherent structures and a fractal domain characterized by the predominantly MHD fluctuations. On the other hand, in regions within the narrow cross-tail current sheet, we expect the spectra to exhibit at least three distinguishable parts: a

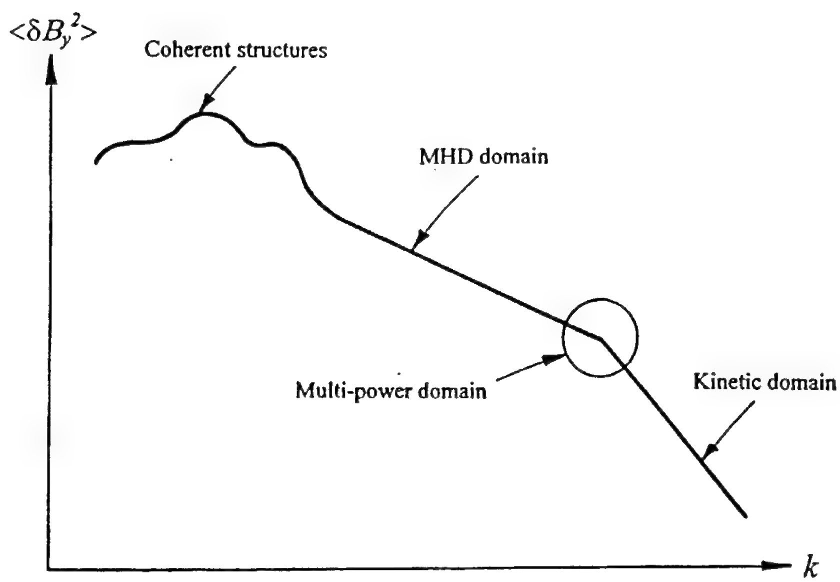

Figure III.2.5: Fluctuation spectrum near the "neutral sheet."

domain that contains predominantly large scale coherent structures, an MHD fractal domain and a kinetic fractal regime whose fractal dimension(s) generally depends on the type(s) of microscopic fluctuations and microinstabilities that are relevant for the merging and diffusion processes. Such type of fluctuation spectra has been recently observed [*Hosino et al.*, 1994; *Milovanov et al.*, 1996; *Zelenyi et al.*, 1998; and references contained therein].

The shapes (slopes) of these spectra in the distant-tail region have been compared with results based on theoretical scaling ideas involving fractal dimensions [*Milovanov et al.*, 1996; *Zelenyi et al.*, 1998]. The difference of slopes of the various domains of an individual spectrum indicates that the scaling (fractal) behavior of each domain belongs to a different "universality class". Such type of change of scaling behavior from one universality class to another is called "symmetry breaking". In addition to the scaling properties of individual discernible domains, there are also intermediate regimes whose fractal properties are much more complicated (as indicated by the circled region of Fig. III.2.5). The scaling laws for these regions are generally expected to exhibit multiple-power or other nonlinear characteristics [*Chang et al.*, 1992].

III.2.6 Summary and Suggestions for Future Research

In summary, we have introduced a multiscale intermittent turbulence model for the dynamics of the magnetotail. The theory is based on the overlapping resonances of plasma fluctuations. It provides a physical picture of sporadic and localized merging of coherent magnetic structures of varied sizes. Such a picture seems to depict the observational properties of "bursty bulk flows" (sporadic localized reconnections) in the magnetotail [*Angelopoulos et al.*, 1996; *Lui*, 1998]. In this picture, the onset of substorm is due to a global nonclassical nonlinear instability and the dynamics of the magnetotail during the evolution of the substorm is characterized by the phenomenon

of forced or self-organized criticality.

The consequence of this is the prediction of multifractal characteristics of the fluctuation spectra [*Hosino et al.*, 1994; *Milovanov et al.*, 1996; *Zelenyi et al.*, 1998; *Chang*, 1992; and references contained therein] and the dynamics of the magnetotail behaves essentially as a low dimensional system. This conclusion seems to agree with the results of some of the recent nonlinear dynamics calculations [*Baker et al.*, 1990; *Klimas et al.*, 1991, 1992, 1998; *Baker*, 1998].

If we accept this new paradigm of magnetotail dynamics, particularly during the periods of substorm evolution, it immediately indicates several new directions of observational, numerical and laboratory investigations.

Observations

In the area of observations, it is obvious that more information in the direction of the fluctuation spectra will be needed. With the limitation of single spacecraft observations, the spectra that can be obtained based on present day observational capabilities will necessarily be restricted within the time domain. To convert these to the **k** spectra, some assumptions will have to be made. In the MHD domain, this is somewhat straightforward since the wave speed is essentially known. For the kinetic region, however, some information with regard to the wave modes must be available. In the future, when sophisticated coordinated multi-spacecraft observations are available, it might be useful to measure the multipoint correlation spectra as well.

It will also be useful if more statistically averaged information is obtained through observations. Since the turbulence is anisotropic and inhomogeneous, directional as well as spatial variations are needed as inputs in the development of specific theoretical calculations. After all, we still need to determine what is (are) exactly the global instability (instabilities) that is (are) responsible for the onset of substorms. There may be several different types of instabilities that can lead to the onset of substorms.

There may also be several different classes of substorms, depending on the input of the global parameters; thereby leading to different characteristics of the fluctuation spectra.

Numerical Simulations

Recent advances in global simulations have given some insights to the nature and characteristics of the global instability (instabilities) that are associated with the onset and evolution of substorms. However, since the global simulations generally depend on ad hoc assumptions of anomalous resistivity or numerically generated dissipation, these numerical results cannot provide any hint to the nature of the true connection between the localized (and at least partially kinetic) dissipative processes and the apparent dissipation that are required in most of the global simulation calculations. Recent numerical simulations of reconnection processes have made numerous advances in the understanding of localized reconnections. These results are particularly useful in the interpretation of the kinetic portion of the fluctuation spectra. However, such information alone will not be sufficient to bridge the gap of the global processes and the localized dissipations. An entirely different class of numerical simulations must be performed. The simulations must address the "large" magnetic Reynolds number problem, and the resulting turbulence must be anisotropic, inhomogeneous, and intermittent such that they are capable of resolving the generation, mixing, and merging of coherent magnetic structures as well as the interaction of these effects with macroscopic and microscopic fluctuations (including particle acceleration and diffusion) during substorms.

Laboratory Simulations

There have been interesting laboratory simulations on magnetic reconnections. For example, there is the admirable work of *Yamada et al.* [1990] on the merging of MHD flux structures, and the equally fine observations on the whistler modes gener-

ated during electron MHD reconnection processes by *Stenzel et al.* [1996]. Gekelman and his collaborators [1997] have been making very interesting and accurate studies of the dynamics and merging of kinetic Alfvén resonance cones. It will be instructive (particularly to the theorists) when the work of Gekelman *et al.* and Stenzel are extended to the nonlinear regime of overlapping kinetic Alfvén and whistler resonances. Ultimately it will be useful in developing larger plasma chambers so that bonafide MHD intermittent turbulence may be conducted.

We conclude this subsection by remarking that a number of the ideas advocated in this research is echoed by a recent insightful book authored by C. Kennel [1995].

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III.3 Recent Developments of Ion Acceleration in the Auroral Zone

Abstract

A brief review of the recent developments in the knowledge of auroral ion acceleration is presented. During the past several years, sufficient experimental data on ion acceleration in the auroral zone have been collected by the Freja satellite, allowing for an in-depth examination of some of the proposed energization mechanisms. In addition, new results from the Akebono, POLAR, and FAST satellites are providing new insights into the details of the microphysics as well as the related mesoscale interactions of ion energization and evolution in the ionosphere and magnetosphere through high-precision and high-resolution measuring instruments. These results are further augmented by a number of equally innovative sounding rocket experiments such as SCIFER and AMICIST. It is not an exaggeration to state that, despite more than twenty years of intense interest and research efforts in ion acceleration, this exotic phenomenon continues to attract the attention and imagination of contemporary auroral physicists.

III.3.1 Introduction

Interest in understanding the fundamental mechanism(s) of ion heating perpendicular to the geomagnetic field in the auroral zone has not waned since the first observations of "ion conics" [*Sharp et al.*, 1977; *Klumpar et al.*, 1979] over two decades ago. The name "conic" refers to the fact that the observed ion distributions are peaked in pitch angle in velocity space. The generally accepted scenario for transverse ion acceleration is some sort of wave-particle interaction. The transversely accelerated ions are then folded into conic shape by the diverging geomagnetic field as they drift to higher altitudes. Candidates of plasma waves that could be responsible for this

process include lower hybrid waves [*Chang and Coppi*, 1981]. electrostatic ion cyclotron waves [*Kindel and Kennel*, 1971; *Palmadesso et al.*, 1974; *Lysak et al.*, 1980; *Ashour-Abdalla and Okuda*, 1984], electromagnetic ion cyclotron waves [*Chang et al.*, 1986; *Temerin and Roth*, 1986], non-resonant static structures and low frequency waves [*Borovsky*, 1984; *Hultqvist*, 1988; *Lundin and Hultqvist*, 1989], and velocity-shear generated localized electrostatic eigenmodes [*Ganguli et al.*, 1994]. Through the years, investigators have come to recognize that, depending on the physical situation, available free-energy, and boundary conditions, nearly all proposed mechanisms are viable processes for transverse ion acceleration. However, only a few mechanisms seem to be of major importance in the terrestrial auroral zone. Sometimes, a combination (or combinations) of these basic mechanisms is needed to provide a reasonable explanation of the observed ion conic distributions.

Since there already exists a number of review articles on this subject [e.g., *Klumpar*, 1986; *Lysak*, 1986; *Chang*, 1993; *André and Chang*, 1993; *André and Yau*, 1997; *Yau and André*, 1997], we shall only briefly touch upon the description of several fundamental heating mechanisms. It is then supplemented by results that are relevant to the more recent observations of the Freja satellite, and the SCIFER and AMICIST sounding rockets. Because of the preliminary and limited nature of the reported data from POLAR and FAST, we shall refrain from making any definitive comments about these results in this review. In some respect, this review may be considered as a supplement to the two previous review articles written by the authors [*André and Chang*, 1993; *Chang*, 1993].

III.3.2 Resonant Heating by Waves Near the Ion Gyrofrequency

A left circularly polarized wave with frequency equal to the ion gyrofrequency can efficiently accelerate a positive ion perpendicularly to a homogeneous magnetic

field. Consider an ion in a homogeneous (infinite wavelength) monochromatic left-handed electric field with frequency f equal to the ion gyrofrequency f_c. Since the electric field rotates in the same direction and with the same angular velocity as the ion, it applies a constant force on the ion along its orbit, providing a velocity increase proportional to the time t; and hence an energy increase proportional to t^2. However, a very narrow-banded coherent wave with frequency around f_c is hard to obtain even in a laboratory, and usually does not occur in the magnetosphere. Rather, random phased waves covering a fairly broad frequency band including f_c are often observed. The left-handed component of these waves still interacts efficiently with the ion. However, the ion motion in velocity space must now be regarded as a random walk. The velocity increase is then proportional to $\sqrt{t}$, and the energy increase is thus proportional to t [*Chang et al.*, 1986]. Broadband waves at frequencies around and below the ion gyrofrequency are often observed in the magnetosphere [e.g., *André et al.*, 1988; *Gurnett et al.*, 1984; *Chang et al.*, 1986]. These waves are often associated with transverse ion heating. Thus, both theory and observations seem to indicate that broadband waves around f_c are important for ion heating.

The theory of ion cyclotron resonance heating by broadband waves is based on a diffusion operator [*Retterer et al.*, 1987]. This operator gives the diffusion rate corresponding to the random walk of ions in velocity space. Using the long wavelength approximation, the operator can be written in a very simple form. This approximation should be valid, for example, for broadband Alfvén waves in most regions of the magnetosphere. The appropriate diffusion coefficient is then simply proportional to the electric field spectral density (S) at the local gyrofrequency of the ion species of interest [*Chang et al.*, 1986; *Retterer et al.*, 1987]. The resulting average heating rate per ion (Q) can also be shown to be proportional to the spectral density (and thus to the mean square of the electric field fluctuations) at the local ion gyrofrequency

[*Chang et al.*, 1986]:

$$Q = (q^2/2m)S_L \tag{III.3.1}$$

where q and m are the charge and mass of the ion, respectively. The spectral density, S_L, in equation (III.3.1) is the fraction of the spectral density due to left-hand polarized waves. Actually the resonance condition $2\pi|f - Nf_c| = k_{||}v_{||}$ should be used to find out at which frequencies (f) ions are in resonance with a wave. Here $k_{||}$ and $v_{||}$ are the parallel wavevector and the parallel component of the particle velocity, while N is an integer. This relation takes into account, e.g., the finite wavelength, and the possibility of interactions at higher harmonics. For emissions with long wavelengths such as most Alfvén waves, the effect of the term $k_{||}v_{||}$ becomes small. Furthermore, interactions at higher harmonics often require a nonzero perpendicular component of the wavevector.

Retterer et al. [1987] applied the cyclotron resonance heating mechanism to observations in the central plasma sheet. In this study, an observed wave spectrum (Fig. III.3.1) together with a Monte Carlo simulation were used to produce an ion distribution quantitatively similar to that observed by *Winningham and Burch* [1984] at a geocentric distance of about 2 earth radii (R_E), Fig. III.3.2. (The theory predicts that the ions were oxygen ions. This prediction was confirmed by measurements from the mass spectrometer EICS on DE-1 [Peterson, Klumpar and Shelley, private communications.]) Other detailed and successful tests of the cyclotron resonance mechanism have been performed using satellite data from the cusp/cleft region [*André et al.*, 1990; *Norqvist et al.*, 1996] and from the nightside auroral region [*Crew et al.*, 1990].

In the central plasma sheet where the ion conics studies by *Retterer et al.* [1987] were observed, there were no obvious local energy sources that could power the broadband electromagnetic waves. This led *Johnson et al.* [1989] to suggest that the waves

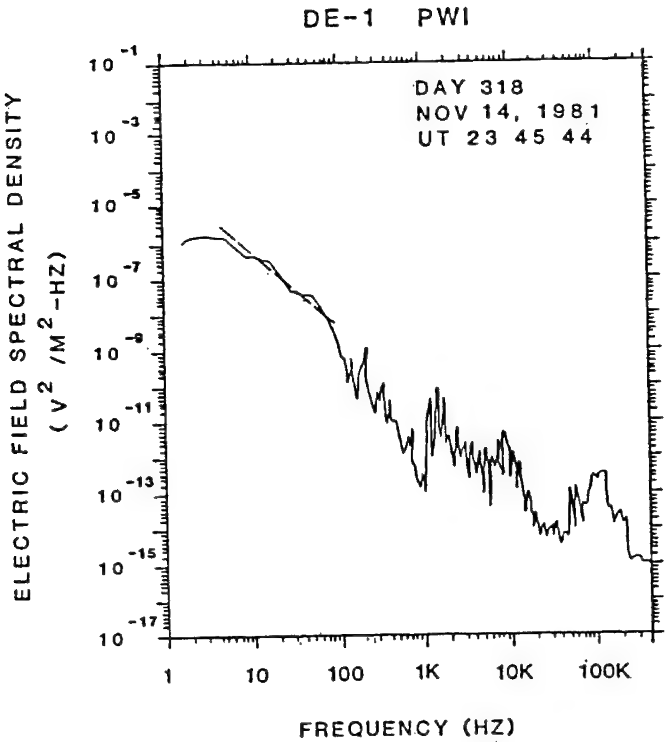


Figure III.3.1: Typical electric field spectral density in the central plasma sheet. Geocentric distance $\approx 2R_E$, invariant latitude $\approx 60°$ (M. Mellott and D. Gurnett, private communication, 1986).

were generated by anisotropic distributions in the equatorial plane and then propagated to the ion heating region. Such a scenario has been demonstrated to be plausible using ray-tracing, wave distribution function, and mode-conversion techniques [*Rönnmark and André*, 1991; *Johnson et al.*, 1995].

Statistical studies of ion mass spectrometer data from both DE-1 [*Peterson et al.*, 1992] and Akebono [*Miyake et al.*, 1996] indicate that ions are not suddenly heated at one altitude and then adiabatically move upward. Rather, the pitch angle of the ion distributions suggest height-integrated transverse acceleration of ions over a wide altitude range. This is consistent with gradual heating, e.g., by waves near the ion gyrofrequency as the ions move upward.

The successful use of relation (III.3.1), and our use of the term "cyclotron reso-

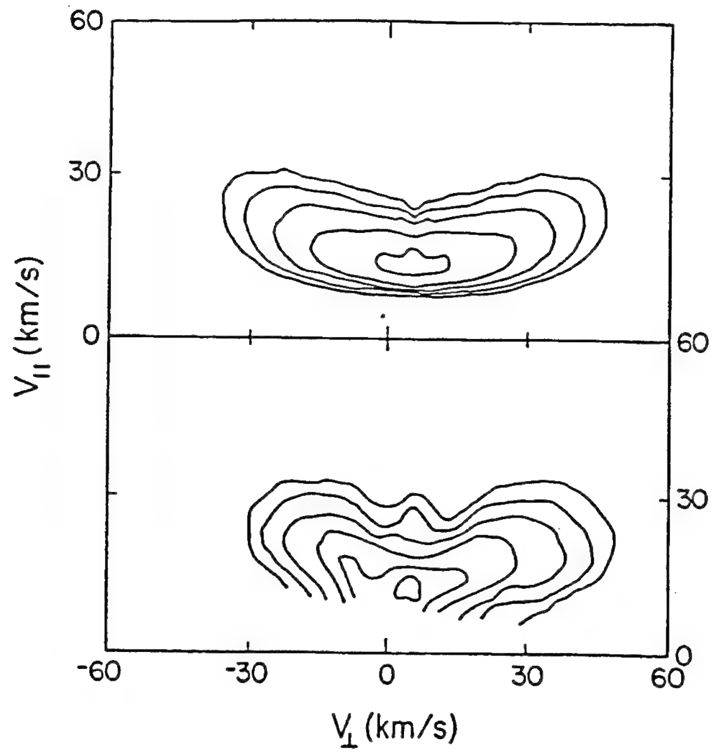


Figure III.3.2: Bottom panel is a contour diagram of the observed ion conic distribution function, measured by the HAPI instrument on the DE-1 satellite [Winningham and Burch, 1984]; the fact that the ions were oxygen ions were confirmed by the EICS instrument on DE-1, (Peterson, Klumpar and Shelley, private communications). Top panel is the calculated ion-velocity distribution [Retterer et al., 1987] using the electromagnetic ion cyclotron resonance theory [Chang et al., 1986] plotted in the same way as the observed distribution.

nance", does not imply that long wavelength Alfvén waves always dominate during the ion heating events. The assumed fraction of left-hand-polarized waves may be regarded as a parameter describing how large fraction of the waves is in resonance with the ions. For various reasons, less than 100% of the observed emissions, which may include so-called electrostatic waves, are in resonance with the ions. Assuming that some fraction of the observed electric field spectral density near the ion gyrofrequency is due to left-hand Alfvén waves is, as a first approximation, the same as assuming that the same fraction of the waves is in resonance with the ions, regardless of the

wave mode.

III.3.3 Resonant Heating by Waves near the Lower Hybrid Frequency

In 1981, Chang and Coppi suggested that under favorable conditions, lower hybrid waves may be responsible for the transverse energization of ionospheric ions in the auroral zone. The original paper assumed a random, broadband wave spectrum. Subsequent theoretical calculations and computer simulations suggest that the broad band turbulence generally is intermittent and inhomogeneous [*Retterer et al.*, 1986; *Chang*, 1993; and references contained therein.] The turbulence may in fact be viewed as an assemble of slowly propagating (i.e., nearly stationary) density cavities filled with emissions near the lower hybrid frequency (lower hybrid cavities.) [See Figure III.3.3.] The theory of Retterer et al. was based on a self-consistent nonlinear theory. Subsequently, *Bell and Ngo* [1990] suggested that such a wave spectrum could also be the results of linear conversion of the often present VLF hiss due to the pre-existing irregularities in the suprauroral region. Generally, the wave-particle interaction process may be relegated to a model diffusion operator [*Crew and Chang*, 1985]. Using such an operator, mesoscale evolution of ionospheric ions in the magnetosphere due to lower hybrid heating may be evaluated [*Retterer et al.*, 1994; *André et al.*, 1994; and references contained therein]. Figures III.3.4 and III.3.5 show simulations and observations of ion distributions heated by waves near the lower hybrid frequency.

Recently, data have been obtained by sounding rockets at altitudes up to 1400 km. Observations by MARIE, sounding rockets in the TOPAZ series, SCIFER and AMICIST indicated that lower hybrid cavities could provide the initial energization of ionospheric ions at low altitudes [*Yau et al.*, 1987; *Kintner et al.*, 1986, *Kintner et al.*, 1992; *Kintner et al.*, 1996; *Arnoldy et al.*, 1996; *Lynch et al.*, 1996]. One

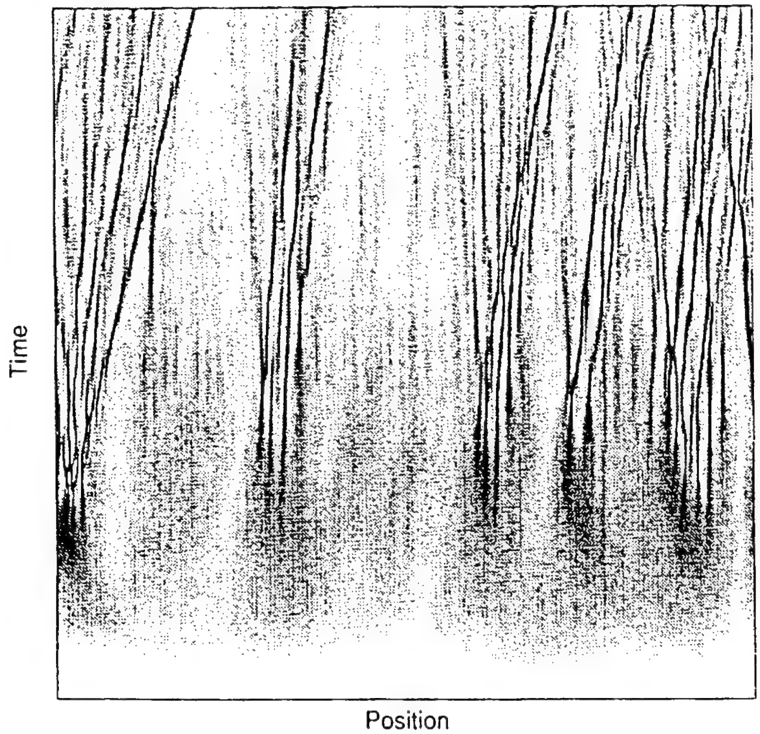


Figure III.3.3: Evolution of lower hybrid caviton turbulence in real space and time based on the theory of Retterer, Chang and Jasperse [1986]. Shading indicates the strength of the electric field amplitude. The horizontal scale is approximately 100 Debye lengths and the vertical scale is approximately 100 ion plasma periods. Notice how the initial nearly uniform wave amplitude intensity evolves into intense localized solitary structures.

possible explanation for the occurrence of these isolated density cavities, in fact, may also be provided by the self-consistent nonlinear picture [*Retterer et al.*, 1994; *Chang*, 1993; *Shapiro et al.*, 1993]. A self-consistent two-dimensional simulation including wave-particle interactions performed by *Retterer* [1997] seems to support these conjectures. Actually, for purely two-dimensional propagations of lower hybrid waves perpendicular to the magnetic field, nonlinear condensation of lower hybrid waves (or lower hybrid collapse) cannot happen. This is proven rigorously by *Tam and Chang* [1995]. However, Tam and Chang have also demonstrated analytically that pseudo two-dimensional collapse can proceed for oblique lower hybrid propagations provided

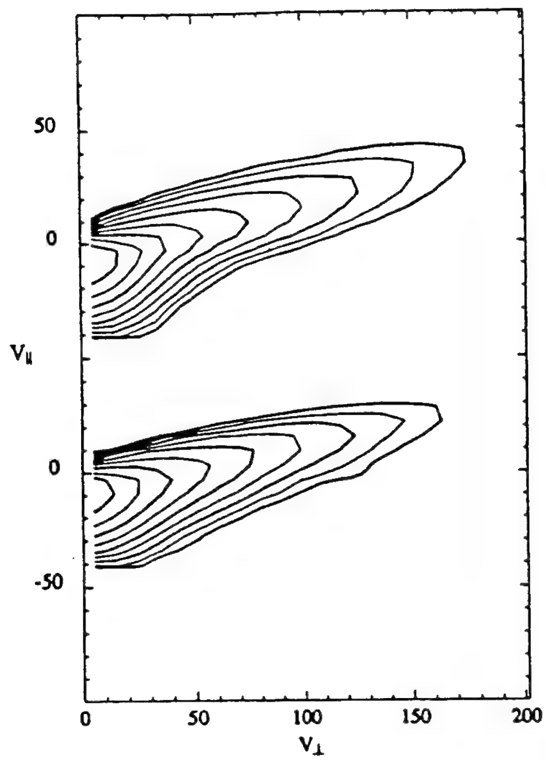


Figure III.3.4: Simulation of the MARIE conic event. Contour plots of the ion distribution as a function of perpendicular and parallel velocities (in km/sec) at 620 km (bottom) and 740 km (top) altitudes. The contours are a half decade apart.

certain propagation characteristics and physical conditions are satisfied. Additionally, as demonstrated by *Retterer et al.* [1994] and *Retterer* [1997], the nonlinear collapse process will generally be arrested by wave-particle interactions.

On the other hand, individual lower hybrid cavities may also result from the trapping of VLF waves in pre-existing density cavities and the subsequent linear conversion into localized lower hybrid eigenmodes [*Seyler*, 1994]. Recently *Pinçon et al.* [1997] and *Schuck et al.* [1997] have shown that the observed oscillations extracted from the TOPAZ data do indeed support the possibility of such an interpretation.

It has been suggested by *Melatos and Robinson* [1996] that for coherent lower hybrid cavities, the ion heating may not be well described by a diffusion operator and transition-time heating theories may need to be employed. On the other hand, the

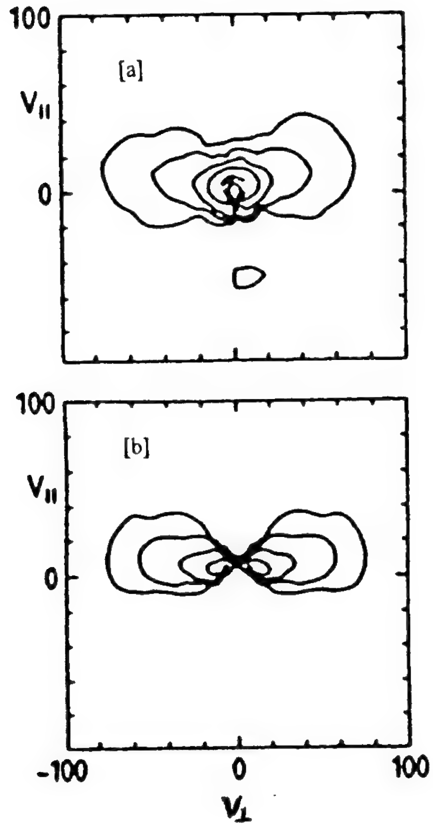


Figure III.3.5: Top panel gives the O^+ distribution function with mean energy of 31 eV obtained by the Freja satellite on orbit 790, December 5, 02.35.20-02.35.32 UT at 1760 km., MLT=18.3 and CGLAT=72.8. Bottem panel corresponds to the O^+ distribution obtained by a Monte Carlo simulation plotted in the same way as the observed distribution.

relative time scales in the auroral zone (where the lower hybrid emissions generally are not truly coherent) seem to indicate that diffusion is the probably the more appropriate wave-particle interaction process to be considered [*Retterer et al.*, 1994].

At higher altitudes, individual lower hybrid cavities have been observed by satellites [*Potellette et al.*, 1992; *Eriksson et al.*, 1994; *Dovner et al.*, 1997]. These lower hybrid cavities are not associated with intense ion heating, but from observations it is hard to exclude the possibility that they could cause ion heating to energies of a few eV.

Although lower hybrid waves are more efficient in heating lighter ions, it has been suggested by *Chang et al.* [1988] and demonstrated by *André et al.* [1994] that oxygen ions may also be heated by broadband lower hybrid waves if these ions were pre-heated by the co-existing broadband waves near the ion gyrofrequency. [See Fig. III.3.5].

III.3.4 Other Heating Mechanisms

A. Multiple Cyclotron and Subharmonic Resonant Heating

It has been suggested by *Temerin and Roth* [1986] that nonlinear resonance could also produce transverse ion heating. One process involves two waves with finite wavenumbers, where the sum of the frequencies matches the gyrofrequency. This mechanism may be called "double cyclotron absorption" (or "double cyclotron resonance"). Assuming low amplitude electric field fluctuations, the average heating rate per ion for this process can be shown to be proportional to the product of the electric field spectral densities at the two frequencies. Although this mechanism is less efficient than the ion cyclotron resonance heating (since it is of higher order in spectral densities), it can involve the entire frequency range (below the local gyrofrequency) of the spectrum and thereby producing a substantial amount of transverse ion acceleration.

A detailed comparison of double-cyclotron absorption with cyclotron resonance heating in the cusp/cleft region of the magnetosphere was performed by *Ball and André* [1991]. This study used the DE-1 data and the heating rates presented by *Ball* [1989a, 1989b]. It was concluded that double-cyclotron absorption might give an appreciable contribution to O^+ energization, especially when the heating was accomplished locally (in altitude). However, the major conclusion is that cyclotron resonance heating is the more efficient mechanism for the oxygen conics observed in the cusp/cleft region.

From a theoretical point of view, there exist obviously other higher order resonance processes involving spectral densities at more than two frequencies ("multiple cyclotron resonance"). However, the heating rates under these circumstances will be of even higher order in wave amplitudes (or spectral densities). For reasonably low wave amplitudes, these higher order effects will be much less efficient and can usually be neglected.

From the discussion above, it follows that waves with frequencies f around the Nth order subharmonic ($f = f_c/N, N = 2, 3, 4 \ldots$) can resonantly heat ions for finite wavelength electric field fluctuations. The average heating rate is then proportional to the Nth power of the electric field spectral density at the subharmonic. For sufficiently low amplitude fluctuating fields, this leads to the following conclusions: (1) Cyclotron resonance ($N = 1$) is, for typical broadband spectra, often more efficient than subharmonic resonances, (2) 2nd order subharmonic resonance heating (which is equivalent to the special case of double cyclotron resonance for $f_1 = f_2 = f_c/2$) is generally more efficient than those due to other higher order subharmonic resonances, and (3) For broadband electric field spectra, it is more important to include all the double cyclotron resonance effects (in addition to the $N = 2$ subharmonic effect) than to include other higher order ($N > 2$) subharmonic effects.

B. Nonresonant Energization

Waves with frequencies much below the ion gyrofrequency may energize ions. Since both the subharmonic heating and multiple cyclotron resonance heating will be of very high order in wave amplitude here, they can generally be neglected. It has been suggested that such waves instead might nonresonantly cause significant ion heating in the magnetosphere [*Lundin et al.*, 1990; *Lundin and Hultqvist*, 1989; *Hultqvist*, 1996].

To test this idea of nonresonant energization, *Ball and André* [1991] performed

waves can heat the ions to the observed energies. However, since the gyrofrequencies of heavy ions are rather low, it will be more difficult to differentiate the contributions of individual energization mechanisms. At least in some instances, double-cyclotron absorption may significantly contribute to O^+ heating [*Ball and André*, 1991]. Similarly, nonresonant interaction with waves below fc may produce significant O^+ heating. Furthermore, such nonresonant energization may well give high enough energies to explain some ion outflow from the ionosphere [*Lundin and Hultqvist*, 1989; *Hultqvist*, 1996]. Nevertheless, *Ball and André* [1991a; 1991b] concluded that energization by waves near the ion gyrofrequency provides the best explanation for the majority of observed ion conic events (that are generated either locally or over an extended region in space) at altitudes above a few thousand kilometers in the auroral and cusp/cleft regions. Recent observations by sounding rockets [*Kintner et al.*, 1996; *Lynch et al.*, 1996] and by Freja [*André et al.*, 1997] indicate that the same type of energization dominates at lower altitudes.

C. Heating at Higher Harmonics

Resonant heating of ions may occur also at higher harmonics of the ion gyrofrequency ($f = Nf_c, N = 2, 3, 4 \ldots$). As in the case of subharmonic heating, energization at higher harmonics requires finite wavelength electric field fluctuations. Heating at higher harmonics is important, e.g., in energization of Tokamak fusion plasmas with radio frequency waves. Here waves are artificially launched on the magnetosonic branch from the low magnetic field side of the plasma. In the magnetosphere, wave absorption at the second harmonic may be important, e.g., when waves are propagating down a magnetic field line, and thus into a stronger magnetic field [*Horne and Thone*, 1990]. In this situation, the frequency of a downgoing wave will first match the second harmonic before reaching the fundamental gyrofrequency. Indeed, in some cases the downgoing wave may be reflected, e.g., at the ion-ion hybrid frequency, be-

fore reaching the gyrofrequency.

For suitable conditions, wave absorption at higher harmonics might be significant. However, for the broadband spectra, which very often are associated with conics, the wave intensity is much higher at the fundamental ion gyrofrequency than at higher harmonics. Thus, resonant heating at the gyrofrequency usually is the more important mechanism. It should be noted that ion energization by waves near the lower hybrid frequency is a special case of heating at higher harmonics. In this case, reasonably high wave intensities occur near the lower hybrid frequency, i.e., usually at several times the ion gyrofrequency. In conclusion, we find that during ion heating events with broadband wave spectra, with a spectral density simply decreasing with frequency, energization by waves at the gyrofrequency dominates over heating at higher frequencies. When waves near the lower hybrid frequency are present, these may cause ion heating via resonant interaction at higher harmonics of the ion gyrofrequency.

D. Low Frequency Electrostatic Waves or Eigenmodes.

One mechanism that has received considerable attention is the heating of ionospheric ions by electrostatic ion cyclotron waves above multiples of the ion gyrofrequency. This possibility was suggested a number of years ago [*Kindel and Kennel*, 1971; *Palmadesso et al.*, 1974] and studied by numerous researchers [*Lysak et al.*, 1980; *Ashour-Abdalla and Okuda*, 1984; and references contained therein]. Electrostatic ion cyclotron waves may be generated by the simultaneously observed upgoing ion beams, or by drifting electrons (currents) in the auroral zone. More recently, it has been suggested by Ganguli [*Ganguli et al.*, 1994; and references contained therein] that electrostatic eignmodes of localized fluctuations in the ion cyclotron [and lower hybrid] range of frequencies may be the prime candidates for the observed electrostatic modes. These fluctuations may be produced locally by velocity-shear

and narrowly confined electric fields. Simulations have demonstrated that these electrostatic eigenmodes can accelerate the ions quite efficiently [*Romero and Ganguli*, 1992, and references contained therein]. Recently, *Kintner et al.* [1996] and *Lynch et al.* [1997] have identified a number of events in the low altitude auroral and cusp/cleft regions where low frequency electrostatic modes are simultaneous observed with the transverse energization of ionospheric ions. These results were based on observations of the SCIFER and AMICIST sounding rocket experiments.

III.3.5 Freja Observations of Various Ion Energization Mechanisms

We conclude this brief review by presenting some recent statistical studies of ion energization events collected by the Freja satellite. The Freja satellite was launched October 6, 1992 into an orbit with 63° inclination, an apogee in the northern hemisphere of 1750 km, and a perigee of 600 km. Data used in the studies described below were obtained in the northern hemisphere at altitudes above about 1450 km. Freja has a set of high-resolution wave instruments [*Marklund et al.*, 1994; *Holback et al.*, 1994; *Zanetti et al.*, 1994] and particle detectors [*Eliasson et al.*, 1994a; *Boehm et al.*, 1994] for studies of space plasma wave-particle interaction processes [*André*, 1993; *Lundin et al.*, 1994a, b]. The spacecraft is Sun-pointing and is spin stabilized with a spin period of 6 s.

Several studies of ion energization events observed by Freja have been performed [*André et al.*, 1994; *Eliasson et al.*, 1994b; *Eriksson et al.*, 1994; *Norqvist et al.*, 1996; *Knudsen et al.*, 1997; *Wahlund et al.*, 1997]. In the following we are mainly interested in intense perpendicular ion energization to mean energies above 5-10 eV. During these events a large fraction of the ions has high enough velocities to eventually escape from the Earth. Studies of several Freja ion heating events show that the most common and important energization mechanism seems to be resonant heating

by broadband low-frequency waves at frequencies of the order of the ion gyrofrequency. At Freja altitudes this mechanism causes the highest number flux of O^+ ions (a few times 10^{13} ions/$(m^2 s)$ on the dayside) and the highest O^+ energies (average energies of up to hundreds of eV, at other local times). The energization occurs within the auroral oval at all local times, and on the nightside the broadband low-frequency waves are loosely associated with keV auroral electrons accelerated by a quasi-static potential drop. However, these waves and the ion energization do not occur on exactly the same field lines as the auroral electrons. Other, less common and less intense, ion energization mechanisms are directly associated with auroral electrons. These electrons may generate waves near the lower hybrid frequency f_{LH} or electromagnetic ion cyclotron (EMIC) waves below the proton gyrofrequency, which then resonantly heats the ions. Yet another possibility is that precipitating H^+ or O^+ ions generate waves near f_{LH} which then locally heat other ions. These latter mechanisms may require "pre-heating" by some broadband low-frequency waves for the ions to obtain high enough velocities to be in resonance with the other wave modes.

When performing a statistical study of perpendicular heating of O^+ ions, *André et al.* [1997] defined a few different types of ion heating regions. Types 1 and 2 are both associated with broadband low-frequency waves. However, Type 1 often occurs adjacent to regions with auroral electrons, while Type 2 is associated with precipitating protons and electrons typical of the cusp/cleft region. Type 3(LH) events occur in regions of auroral electrons and waves near the lower hybrid frequency, while Type 3(EMIC) also is directly associated with auroral electrons but with EMIC waves at about half the proton gyrofrequency. During Type 4 events precipitating ions (H^+ or O^+) with keV energies are correlated with ion heating, and the events are different from Type 2 events typical of the cusp/cleft region, e.g., since no precipitating electrons are observed. One objective of the study was to investigate the relation

between wave intensity at various frequencies and the O^+) mean energy. The basic idea was to perform a test to see if the observed wave intensities at some resonant wave frequencies were high enough to cause the observed ion energies. Accordingly, a total of 20 events of intense ion energization were selected. During each event, twelve satellite spin periods of six seconds, each corresponding to about 40 km along the spacecraft orbit, were studied in detail. The periods were chosen either within the regions of intense ion heating, or near but outside the heating region. The O^+ mean energy W_{O^+} (obtained by integrating over perpendicular velocities) as a function of electric field spectral density at 25 Hz (close to the O^+ gyrofrequency at these altitudes), S_E(25Hz), for the Type 1 and 2 events is given in Figure III.3.6a. In Figure III.3.6a it is obvious that high (low) wave intensities correspond to high (low) ion mean energies. Rather than just investigating the correlation between ion and wave observations, we also estimate the O^+ energies that can be obtained from the waves. To do so, we use the ion cyclotron resonance heating mechanism [*Chang et al.*, 1986]. A maximum heating rate corresponding to waves with frequencies covering the ion gyrofrequency can be obtained by assuming that the perpendicular wavevector is much smaller than the inverse of the ion gyroradius (as would be the case for some Alfvén waves), and that the left-hand polarized fraction of the waves is heating the ions. The ion cyclotron heating rate [*Chang et al.*, 1986; *Retterer et al.*, 1987] is then given by Eq. (III.3.1) of Section III.3.2. This relation is convenient to use when estimating the ion heating rate from the observed spectral densities. An exact calculation of the ion energies that can be caused by the observed waves requires detailed information concerning the waves, such as distribution in wavevector space, which usually is not available. The successful use of relation (III.3.1) in several studies is not necessarily an indication that the long wavelength Alfvén wave is the dominant wave mode in the observed broadband low-frequency spectra. For example, recent

[a]

[b]

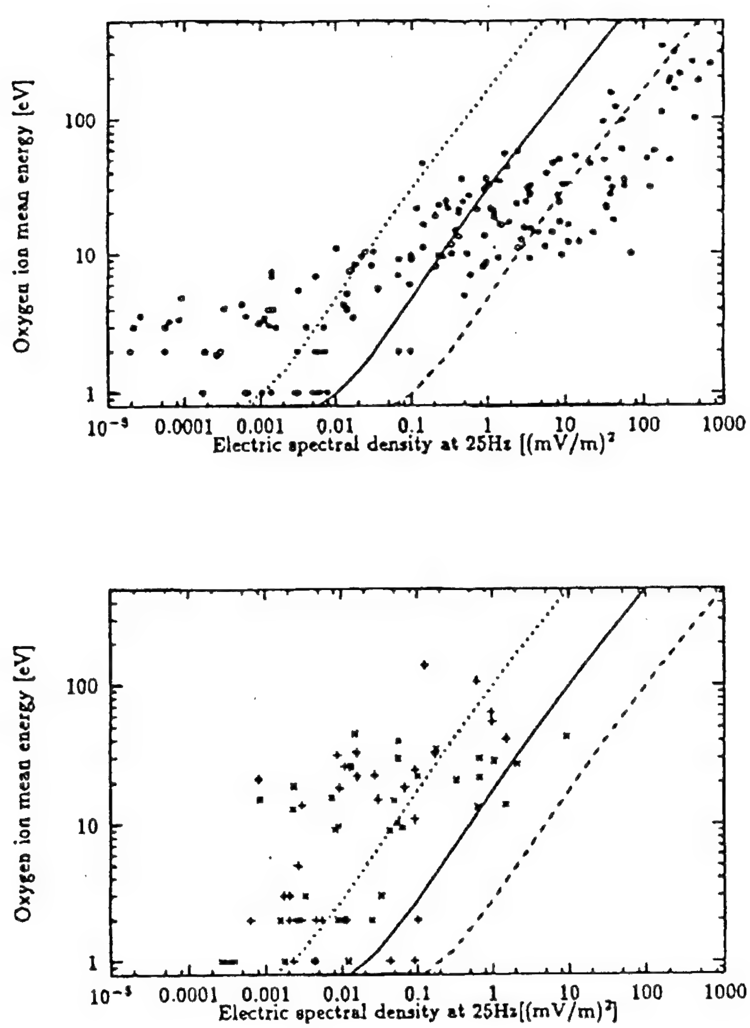


Figure III.3.6: Mean perpendicular O^+ energy as a function of electric field spectral density at 25 Hz (approximately the oxygen gyrofrequency) for (a) Type 1 and 2 ion heating events, and for (b) Type 3(LH) and 3(EMIC). Each data point corresponds to observations from a six second period. The dashed, solid and dotted lines correspond to ion mean energies that can be obtained from cyclotron heating at 25 Hz when 1%, 10% and 100% (respectively) of the observed spectral density contributes to ion energization. The ions are launched at 300 km below the satellite. Essentially all points in (a) with energies above 5-10 eV can be explained by resonant cyclotron heating, while this is not the case for (b).

studies indicate that a significant fraction of these emissions sometimes may be ion acoustic waves [*Wahlund et al.*, 1997] or electrostatic ion cyclotron waves [*Bonnell et al.*, 1996]. The simple cyclotron heating mechanism can nevertheless be useful when estimating the effects of observed waves on the ions. Assuming that some fraction, which must be less than 100%, of the observed electric field spectral density near the ion gyrofrequency is due to left-hand Alfvén waves is, as a first approximation, the same as assuming that the same fraction of the waves are in resonance with the ions, regardless of wave mode.

The lines in Figure III.3.6a give an estimate of the ion energies expected from the cyclotron resonance mechanism. The expected energies have been estimated from test particle calculations [*Chang et al.*, 1986]. The particles are started 300 km below the satellite, as indicated by the folding of the observed O^+ distributions. The initial energy and pitch-angle is taken to be 0.5 eV and 135° respectively, but the final O^+ energy is not sensitive to these two parameters. To be able to map the spectral density at the local oxygen gyrofrequency to a lower altitude, the spectral density is approximated by a power law $S_E(f) = S_0(f_0/f)^\alpha$ where S_0 and f_0 are constants, f is the frequency and α is a model spectral slope [*Chang et al.*, 1986]. We always use $\alpha = 1$, but the result is not sensitive to this parameter since the altitude range is small. Following the particles in a dipole geomagnetic field, the three lines in Figure III.3.6a can be obtained. These lines correspond to some fraction (100%, 10% or 1%) of the spectral density being in resonance with the ions.

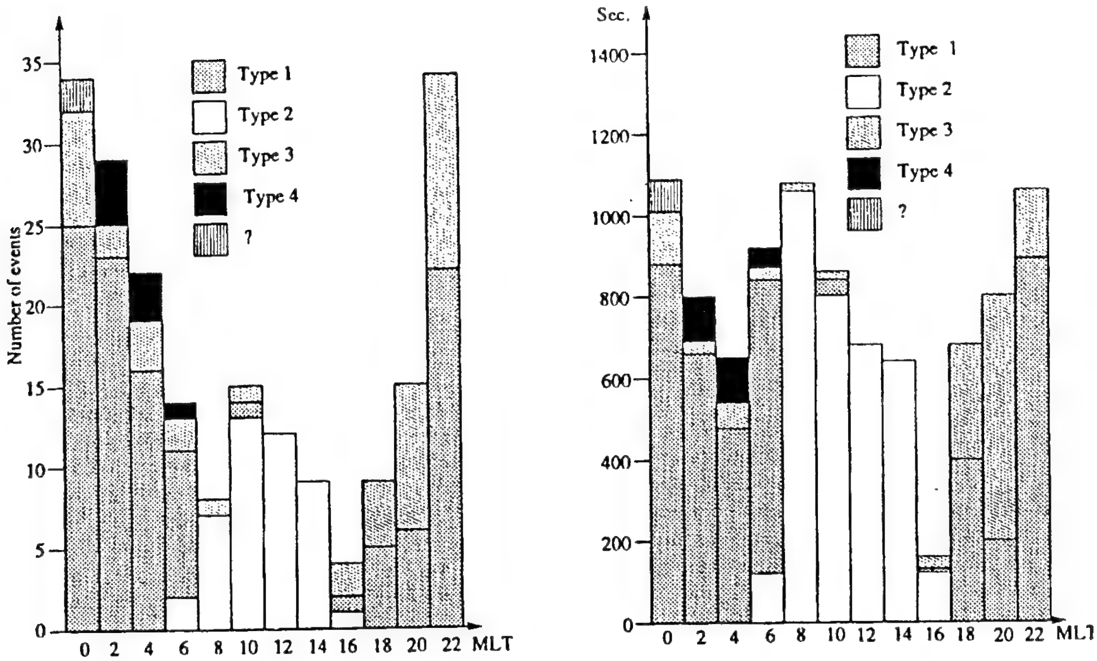
It is clear that for ion energies above 5–10 eV essentially all data points in Figure III.3.6a are consistent with heating by less than 100% of the observed waves. Thus Figure III.3.6a is consistent with the observed O^+ ions being energized by the observed waves with frequencies around f_{O^+}.

Ion energies below 3–5 eV in Figure III.3.6a are uncertain due to effects such as

spacecraft motion and charging. The fact that several mean energies are displayed at exactly one, two or three eV is artificial. There is a threshold at spectral densities of 10^{-3} to $10^{-2}(\mathrm{mV/m})^2/\mathrm{Hz}$ above which ion mean energies below a few eV only rarely occur. This is consistent with the cyclotron resonance mechanism, and also with a study using the cold plasma analyzer on Freja [*Knudsen et al.*, 1997].

So far we have considered only Type 1 and 2 events. All these ion heating events are associated with broadband electric field waves, and these waves include high intensities at 25 Hz. We now instead investigate all Type 3 (both 3(LH) and 3(EMIC)) events. Figure III.3.6b is similar to Figure III.3.6a but shows mean O^+ energy as a function of S_E(25Hz) for Type 3 events. It is obvious that many data points can not be explained by the cyclotron resonance mechanism. For several other points the cyclotron mechanism might be significant. At least for some points a combination of heating by waves near f_{O^+} and near the lower hybrid frequency may be important [*André et al.*, 1994]. In summary we find that waves near f_{O^+} can not explain all ion energization during Type 3 events. Above we have concentrated on the heating that can be caused by waves near f_{O^+}. Similar studies of EMIC waves near the half the proton gyrofrequency, show that during Type 3(EMIC) events the observed EMIC can cause the observed O^+ ion energies. Similarly, investigations of waves near the lower hybrid frequency clearly indicate that during Type 3(LH) events these waves can energize the observed ions. Also, during most Type 3 events, it is not likely that the (often weak) broadband low-frequency waves that are present can cause the ion heating, but the other observed wave emissions are really needed to explain the observed ion energies.

To investigate the relative importance of ion energization by waves at different frequencies, a preliminary statistical study was performed by using Freja data from the November 18, 1993 to March 8, 1994 (orbits 5390 to 6850) [*André et al.*, 1997].



[a] [b]

Figure III.3.7: Different types of ion heating events obtained by the Freja satellite near 1700 km during approximately 1300 passes over some ground station. (a) Number of events. (b) Number of seconds spent in each type of event. Type 1 and 2 are both associated with broadband low frequency waves. Type 3 is connected with auroral electrons and waves near half of the hydrogen gyrofrequency or waves around the lower hybrid frequency, while type 4 is associated with precipitating H^+ or O^+ ions and, again around the lower hybrid frequency.

This period gives approximately equal coverage of all magnetic local times. Nearly all events with O^+ mean energies above 5–10 eV could be classified as belonging to one of the previously discussed Types of ion energization. In this study, the events of Types 3(EMIC) and 3(LH) could not be separated, and were all categorized as Type 3. Figure III.3.7a shows the number of different types of events as a function of Magnetic Local Time. Figure III.3.7b displays the number of seconds spent by Freja in various types of ion heating events, again as a function of MLT. This latter figure gives an estimate of the overall importance (the linear dimension perpendicular to the

geomagnetic field) of the various types of events. This preliminary statistical study clearly indicates that events where broadband low-frequency waves are associated with ion heating (Types 1 and 2) are more common than events involving waves near the lower hybrid or EMIC emissions near half the proton gyrofrequency (Type 3 and also Type 4).

The Freja observations are similar to recent sounding rocket observations. Observations by the SCIFER sounding rocket at 1400 km and near 10:00 Magnetic Local Time (MLT) in the cleft again shows ion energization clearly associated with broadband low-frequency waves [*Kintner et al.*, 1996; *Moore et al.*, 1996; *Arnoldy et al.*, 1996]. The energization is associated with clear density depletions with sharp boundaries. These density depletions are tens of kilometers in the perpendicular direction. The depletions are consistent with even larger regions of low plasma density, broadband low-frequency waves and ion heating observed by the Viking [*Hultqvist*, 1991] and Freja satellites [*Lundin et al.*, 1994c; *André et al.*, 1997] at altitudes up to 13500 km (Viking apogee). These ion heating events occur at various local times, and similar ion energization in a sharply confined spatial region poleward of a nightside auroral arc has recently been observed by the AMICIST sounding rocket at 900 km, near 23:00 MLT [*Lynch et al.*, 1997]. The AMICIST rocket also observed heating by lower hybrid emissions confined in narrow density depletions, so-called lower hybrid cavities. However, the ion outflow from the region with broadband low-frequency waves was significantly larger than the outflow associated with lower hybrid waves. Thus both Freja and sounding rocket data indicate that regions with broadband low-frequency waves are most important for ion energization and outflow.

III.3.6 Epilog

In this write-up, we have endeavored to provide a brief summary of several viable

mechanisms for the transverse heating of ionospheric ions in the auroral and cusp/cleft regions. These ideas are brought into focus with data collected by Freja, SCIFER and AMICIST. We have not discussed all the possible heating mechanisms. For example, there are no discussions given for the stochastic heating by coherent waves or random scattering of ions by solitary kinetic Alfvén waves. Our selection of ion heating has been strongly guided by spacecraft observations. Data from various satellites and sounding rockets indicate that resonant heating by waves near the appropriate ion gyrofrequency is the dominant energization mechanism in the auroral region.

New data that are being collected by the recently launched satellites, POLAR and FAST, will certainly provide additional new insights into the fundamental processes of ion heating. Indeed, results from FAST seem to indicate that sporadic localized (linear or solitary) wave modes contribute to the fundamental energization process of the ions as well as electrons. Due to the preliminary nature of the new results, however, we have refrained from discussing these topics. Finally, most of the theories of mesoscale evolution of ion heating assume a given plasma background. Self-consistent calculations that address both the inhomogeneous plasma background and the microscopic interactions are ultimately needed. Some calculations aiming in that direction have been made recently [*Ganguli et al.*, 1992; *Horwitz*, 1995; *Brown et al.*, 1995; *Tam et al.*, 1995].

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III.4 New Results of the Theory of Non-Classical Polar Wind

Abstract

Recent *in situ* observations have revealed novel features in the polar wind. Measurements between 5000 and 9000 km altitude by the Akebono satellite indicate that both H^+ and O^+ ions have remarkably higher outflow velocities in the sunlit region than on the nightside. Electrons also display an asymmetric behavior: the dayside difference in energy spread, greater for upward-moving than downward-moving electrons, is absent on the nightside. Our previous calculations based on a self-consistent hybrid model [*Tam et al.*, 1995b] have demonstrated the significance of the anisotropic kinetic effects of photoelectrons in the dayside polar outflow. Results generated from the model agree with various qualitative features observed in the sunlit polar region by the Akebono satellite. Our recent work has extended the application of the model to the night-side polar outflow, in which photoelectrons are practically absent. By comparing the daytime and night-time results of our model, we demonstrate the anisotropic kinetic photoelectron effects on the polar outflow. In particular, the presence/absence of these suprathermal electron effects is responsible for the polar wind day-night asymmetries observed by the Akebono satellite.

III.4.1 Motivation

The existence of the polar wind, an outflow of plasma along the open magnetic field lines emanating from the polar region of the ionosphere, was first proposed by *Axford* [1968] and *Banks and Holzer* [1968]. These early studies recognized the ambipolar electric field as one of the mechanisms governing the plasma outflow. Because the polar cap, in general, is a relatively quiescent region, the ambipolar effect is a major contribution to the electric field in the "classical" polar wind, the steady-state, quasi-

neutral, current-free outflow of plasma.

The ambipolar field itself exists self-consistently with the background plasma. It is therefore influenced by other mechanisms that need to be included in the dynamics of the particles. For example, the geomagnetic field, which decreases with altitude, gives rise to the mirror force that changes the particles' pitch angles. Coulomb interactions among all the species lead to energy exchange and pitch angle diffusion. These effects are essential to the dynamics of the particles, and therefore, can affect the polar wind electric field.

Recent observations have suggested that another effect, photoelectron populations generated in the sunlit ionosphere, can alter the polar wind significantly. Our study on the photoelectron-driven polar wind is motivated by these increasingly convincing experimental indications.

Early polar cap measurements obtained by the ISIS-1 satellite showed evidence of "anomalous" field-aligned photoelectron fluxes in both upward and downward directions, where the downgoing (return) fluxes were considerably smaller than the outgoing fluxes above a certain energy [*Winningham and Heikkila*, 1974]. Such non-thermal features were confirmed by the DE-1 and -2 satellites [*Winningham and Gurgiolo*, 1982]: outgoing field-aligned electron fluxes in the photoelectron energy range were observed by the HAPI (High Altitude Plasma Instrument) on DE-1 and the LAPI (Low Altitude Plasma Instrument) on DE-2; evidence of downstreaming electron fluxes was also found in the low-altitude distribution measured by the LAPI. These fluxes are considered anomalous because their existence cannot be related to the idea of thermal conductivity and temperature gradient in classical fluid theories. Similar to the ISIS-1 measurements, the return fluxes observed by DE-2 were comparable to the outgoing fluxes below some truncation energy, but considerably smaller above that. As suggested by *Winningham and Gurgiolo* [1982], the existence

of such downstreaming fluxes may be due to reflection of electrons by the ambipolar electric field along the geomagnetic field line above the satellite. The truncation energy, obtained by comparing the outgoing and the return electron fluxes, would thus provide an estimate for the potential drop due to the electric field. These authors observed that this truncation energy ranged from 5 to 60 eV, and thus were able to deduce the magnitude of the potential drop above the altitude of the satellite ($\sim$ 500 km). Unfortunately, existing classical polar wind theories can only account for a much smaller potential drop [*Ganguli*, 1996; and references therein]. *Winningham and Gurgiolo* [1982] also pointed out that variation of the truncation energy was due to changes in the solar zenith angle at the production layer below the satellite. The solar zenith angle is related to the photoionization rate, which itself is related to the local ionospheric photoelectron density [*Jasperse*, 1981]. These observations therefore imply a relationship between the local photoelectron density below the satellite and the potential drop along the field line above it, and are consistent with the idea that the photoelectrons may significantly affect the ambipolar electric field.

While the observations discussed above have implied that photoelectrons may contribute to the dynamics of the polar wind, more recent evidence indicates that the polar wind characteristics themselves are affected by the photoelectrons. *In situ* measurements by the Akebono satellite have revealed novel features in the polar wind: day-night asymmetries in the ion and electron features. The most dramatic are asymmetries in the ion outflow velocities [*Abe et al.*, 1993b]: satellite data between 5000 and 9000 km altitude have indicated remarkably higher outflow velocities for the major ion species, H^+ and O^+, in the sunlit region than on the nightside. For example, the H^+ velocity (u_h) was found to be about 12 km/s on the dayside, but only about 5 km/s on the nightside. Similarly, the O^+ velocity (u_o) in the sunlit region ($\sim$ 7 km/s) is about twice that in the midnight sector ($\sim$ 3 km/s). A day-night

asymmetry was also observed in the electron behavior. Electrons were distinguished according to their velocities along the geomagnetic field line. On the dayside, it was found that the temperature of the upstreaming population is greater than that of the downstreaming population, *i.e.*, $T_{e,up} > T_{e,down}$, indicative of an upwardly directed heat flux [*Yau et al.*, 1995]. On the nightside, in contrast, no such up-down anisotropy was observed [*Abe et al.*, 1996].

Besides the day-night asymmetries, Akebono measurements between 5000 and 9000 km altitude have also revealed other sometimes unexpected ion transport properties in the polar region [*Abe et al.*, 1993b]. For example, O^+ was most often found to be dominant over H^+ as the major ion species, contrary to the traditional belief that very few O^+ ions are able to overcome the gravitational force and escape to such high altitudes due to their heavier mass. The measured outflow velocities for both the H^+ and O^+ ions in general increase monotonically with altitude, and the flows for both species are supersonic at high altitudes. In fact, the measured O^+ outflow velocities (see above) are much larger than the values expected by classical polar wind models [e.g., *Schunk and Watkins*, 1981, 1982; *Blelly and Schunk*, 1993]. All these ion outflow characteristics, particularly the enhanced ion outflow velocities, suggest a higher ambipolar electric field than that predicted by classical polar wind models [*Ganguli*, 1996; and references therein], and are consistent with the values of the field-aligned potential drop deduced by *Winningham and Gurgiolo* [1982] based on the DE-2 measurements.

Because of the marked day-night asymmetries observed in several characteristics of the polar wind, and the fact that photoelectrons exist primarily in the sunlit ionosphere, they are *the* natural candidate to account for the day-night asymmetries. Indeed, collisionless kinetic calculations by *Lemaire* [1972] showed that escaping photoelectrons may enhance the electric field and increase the ion outflow velocities in

the polar wind. Photoelectrons, therefore, may provide a possible explanation for the observations of both sets of satellites: the magnitude of the ambipolar electric field deduced from the DE-2 measurements, and the day-night asymmetries and enhanced ion outflow velocities observed by the Akebono satellite. Because Coulomb collisions may also influence the dynamics of the photoelectrons, for example, by transferring their energy to other particle components in the polar wind, and thereby reducing the escaping photoelectron flux, collisional effects should also be taken into account in determining the impact of photoelectrons on the electric field. Our goal, therefore, is to address these observations by incorporating the complete photoelectron physics into a self-consistent, global description of the polar wind.

III.4.2 Photoelectrons, Energy Fluxes and Electric Field

The global kinetic collisional physics of suprathermal electrons in a steady-state space plasma outflow was first considered by *Scudder and Olbert* [1979] in their study of the solar wind halo electrons. These authors related the anomalous field-aligned electron heat fluxes observed in the solar wind to the non-local nature of the electron distributions, and demonstrated the formation of such non-thermal features using a simplified collisional operator. They also suggested that these suprathermal electrons, through their anomalous contribution to the energy flux, may significantly increase the ambipolar electric field along the magnetic field lines, thereby "driving" the solar wind [*Olbert*, 1982].

An analogous situation exists for the dayside, photoelectron-driven polar wind. It has been shown by *Yasseen et al.* [1989] that the polar wind photoelectrons can give rise to the non-thermal distributions observed by the DE satellites [*Winningham and Gurgiolo*, 1982]. The effect on the polar wind due to the energy fluxes associated with these photoelectrons has been examined by *Tam et al.* [1995a], who

concluded that such anomalous electron energy fluxes may significantly increase the ambipolar electric field. Because photoelectrons exist primarily in the sunlit ionosphere, they enhances the dayside ambipolar electric field, thereby increasing the ion outflow velocities on the dayside. Photoelectrons, with their associated energy fluxes, can therefore provide not only a mechanism for the enhanced ion outflow velocities observed by the Akebono satellite [*Abe et al.*, 1993a,b], but also the explanation for the observed day-night asymmetric ion and electron features in the polar wind [*Abe et al.*, 1993b, 1996; *Yau et al.*, 1995].

Energetic suprathermal electrons in the polar wind or in other ionospheric/ magnetospheric settings have been considered by various authors. For example, kinetic collisional calculations by *Khazanov et al.* [1993] have examined the role of photoelectrons on plasmaspheric refilling. Collisionless kinetic calculations by *Lemaire* [1972] have shown that escaping photoelectrons may increase the ion outflow velocities in the polar wind. Collisionless kinetic calculations by *Barakat and Schunk* [1984] and generalized semi-kinetic (GSK) calculations by *Ho et al.* [1992] have examined the impact of hot magnetospheric electrons, and concluded that such particles may also increase the ion outflow velocities.

We should add that other mechanisms besides suprathermal electron effects may also be proposed as alternative explanations for the enhanced ion velocities. Parallel ion acceleration driven by $\mathbf{E} \times \mathbf{B}$ convection was considered by *Cladis* [1986], and shown to significantly energize O^+ ions escaping to the polar magnetosphere. This force can also be seen as a centrifugal force in the convecting frame of reference, and was included in this form in the time-dependent, GSK model developed by *Horwitz et al.* [1994]. These mechanisms, including the suprathermal electron effects, have been reviewed by *Ganguli* [1996].

A self-consistent hybrid model has been developed by *Tam et al.* [1995b] to take into account the global kinetic collisional nature of the polar wind physics introduced

by the photoelectrons. The details and advantages of the model have recently been discussed by *Tam et al.* [1998b]. The results presented in this report are based on the model. The model represents two breakthroughs in polar wind theoretical modeling. One, it was the first to successfully incorporate the global kinetic collisional photoelectron effects into a self-consistent polar wind description. Two, due to its kinetic treatment of the ions, the model was the first to generate self-consistent global polar wind calculations whose solutions span continuously from a collisionless subsonic regime at low altitudes to a collisional supersonic regime at high altitudes.

The model is hybrid in that it consists of a kinetic and a fluid component. Photoelectrons (treated as test particles because of their low relative density) and both the H^+ and O^+ ions are described using a global kinetic collisional approach while thermal electron properties (density, drift velocity, and temperature) are determined from a simpler, fluid approach that also calculates the self-consistent ambipolar electric field. Because of its treatment of the thermal electrons, the model should be distinguished from traditional hybrid approaches where electrons are treated as a massless neutralizing fluid. The model is based on an iterative scheme combining the kinetic and fluid calculations, that should converge to physically meaningful solutions.

Let us specify some criteria that will enable us to define more precisely our study of the polar wind. First, we will consider the polar wind only at altitudes above 500 km (which corresponds roughly to the polar orbits of DE-2). At such altitudes, neutral densities are low enough to neglect the "chemical" reactions such as photoionization, recombination, *etc.* Second, the magnitude of the geomagnetic field is such that the gyration period and Larmor radius, for all particle species, are much smaller than any relevant time or length scales. We can therefore use the guiding center approximation. Third, the gradients of the geomagnetic field are such that only transport *along* the geomagnetic field line is important. The time-dependent

distribution function $f(t, s, v_{\|}, v_{\perp})$ for a given particle species is therefore governed by the following collisional gyrokinetic equation:

$$\left[\frac{\partial}{\partial t} + v_{\|}\frac{\partial}{\partial s} - \left(g - \frac{q}{m}E_{\|}\right)\frac{\partial}{\partial v_{\|}} - {v_{\perp}}^{2}\frac{B'}{2B}\left(\frac{\partial}{\partial v_{\|}} - \frac{v_{\|}}{v_{\perp}}\frac{\partial}{\partial v_{\perp}}\right)\right] f = \frac{\delta f}{\delta t} = Cf, \tag{III.4.1}$$

where s is the distance along the magnetic field line B, q and m are the algebraic electric charge and mass of the species respectively, $E_{\|}$ is the field-aligned electric field, g is the gravitational acceleration, $B' \equiv dB/ds$, $\delta f/\delta t$ represents the rate of change of the distribution function due to collisions, and C is a collisional operator for Coulomb interaction, which is the dominant type of collision above 300 km altitude. Note that the operator C for a given particle species describes not only Coulomb collisions with other species, but also those among the same species itself. Equation (III.4.1) thus includes all the major forces a particle experiences as it travels along the geomagnetic field line: gravitational force, field-aligned electric force, mirror force, and forces that are due to Coulomb collisions, including those with the same species. The time-independent version of Eq. (III.4.1) is the governing equation in the kinetic component of our model.

III.4.3 Day-Night Asymmetries in the Polar Outflow

Our main goal is to demonstrate the observed day-night asymmetry of the polar outflow based on our study of the anisotropic kinetic photoelectron effects. Application of the self-consistent hybrid model to the sunlit polar region has generated results [*Tam et al.*, 1998b] that are qualitatively and quantitatively consistent with polar wind observations [*Abe et al.*, 1993b; *Yau et al.*, 1995]. In this study, we characterize the night-time polar wind conditions with the absence of photoelectrons. Thus, we generate a night-time polar outflow solution by using the same boundary conditions as those for the daytime, except without the presence of photoelectrons, *i.e.*

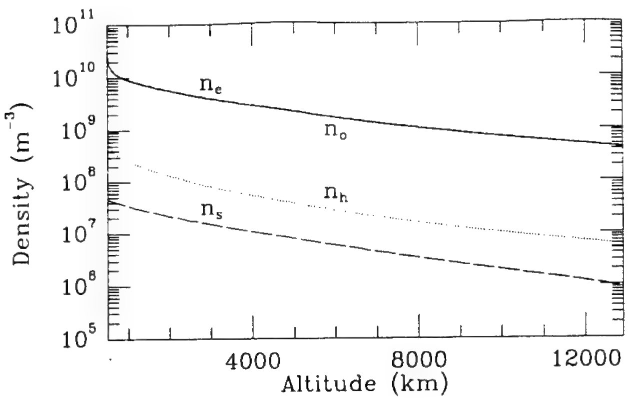

Figure III.4.1: Density profiles for O^+ (n_o), H^+ (n_h), thermal electron (n_e), and photoelectron (n_s) in the dayside polar wind solution. Note that n_e and n_o are almost equal because of quasi-neutrality. Their lines virtually overlap in the plot.

$n_s = 0$.

The density profiles of all the species in the daytime polar wind solution is shown in Fig. III.4.1. Note that the photoelectron density n_s is small compared with the thermal electron density n_e. Our test-particle approach for photoelectrons is therefore justified. The small photoelectron density, however, does not imply that these suprathermal particles are insignificant to the overall polar outflow dynamics. Because of the relation between the electron energy flux (or heat flux) and the ambipolar electric field [*Tam et al.*, 1995a], one has to examine the photoelectron heat flux contribution as well in order to determine whether the suprathermal population can significantly affect the outflow dynamics. Fig. III.4.2 shows a typical normalized distribution for the combined electron population in our dayside solution. The contributions from the thermal and photoelectrons are also plotted in the figure. Note that the tail portion of the distribution is dominated by the photoelectron population. Such a distribution suggests that the majority of the electron heat flux is carried by the photoelectrons. By comparing the heat flux contribution due to the thermal electron with that carried by the photoelectrons, we find that the heat fluxes carried by the two electron components are in opposite directions: downward for the thermal

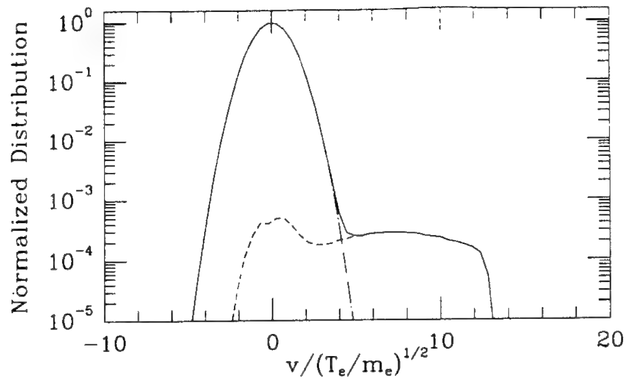

Figure III.4.2: A typical normalized distributions for the combined electron population (thermal and photoelectrons) in the dayside polar wind (solid line). Dot-dashed line is for the thermal electron distribution; dashed line is for the photoelectrons. The distributions were calculated at 7500 km altitude. T_e is the temperature of the thermal electron population, and m_e is the electron mass.

but upward for the suprathermal, as shown in the top panel of Fig. III.4.3. We also find that the photoelectron heat flux is much larger in magnitude than its thermal counterpart, as shown in the bottom panel of Fig. III.4.3. The two heat flux components combine to give the total electron heat flux whose direction is dictated by the photoelectron contribution, *i.e.* upward. The upwardly directed total electron heat flux is consistent with the data from *Yau et al.* [1995] and the results by *Tam et al.* [1995a,b].

Due to the upwardly directed heat flux associated with the kinetic nature of photoelectrons, we expect the self-consistent ambipolar electric field to be larger in the dayside polar wind. That would give rise to a larger potential difference on the dayside, as compared with the nightside where photoelectrons are absent. Fig. III.4.4 shows the self-consistent electric potential profiles for both polar wind solutions. The potential drop in the dayside solution is about 5 V, which is considerably larger than that on the nightside (about 2 V), and is comparable to value deduced from observations [*Winningham and Gurgiolo*, 1982].

The magnitude of the self-consistent ambipolar electric field has a significant im-

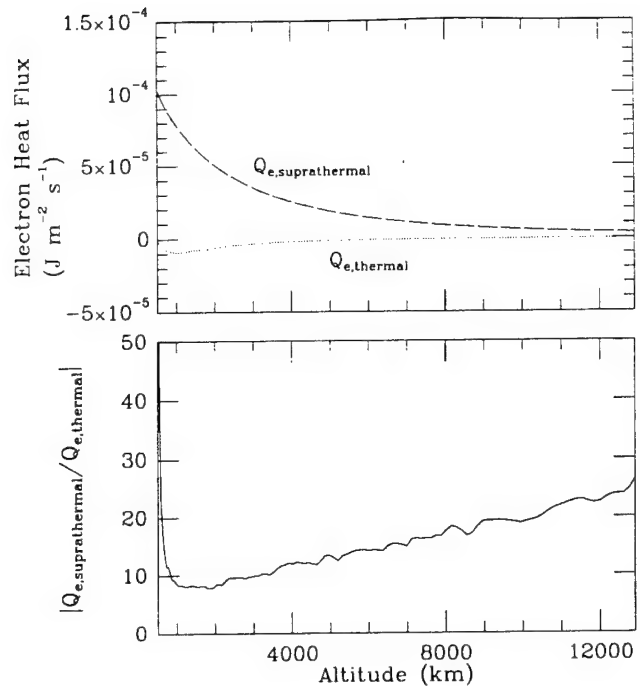

Figure III.4.3: Top panel: heat fluxes carried by the thermal electrons ($Q_{e,thermal}$) and photoelectrons ($Q_{e,suprathermal}$) in the dayside polar wind solution. Note that the heat flux contribution by the thermal electrons is in the downward direction (negative sign) while that by the photoelectrons is upwardly directed (positive sign). Bottom panel: the ratio of the magnitudes of the two heat fluxes.

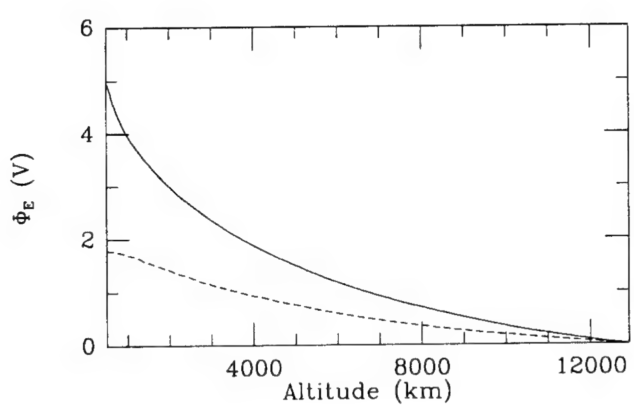

Figure III.4.4: Self-consistent ambipolar electric potential profiles in the dayside (solid) and nightside (dashed) polar wind solutions.

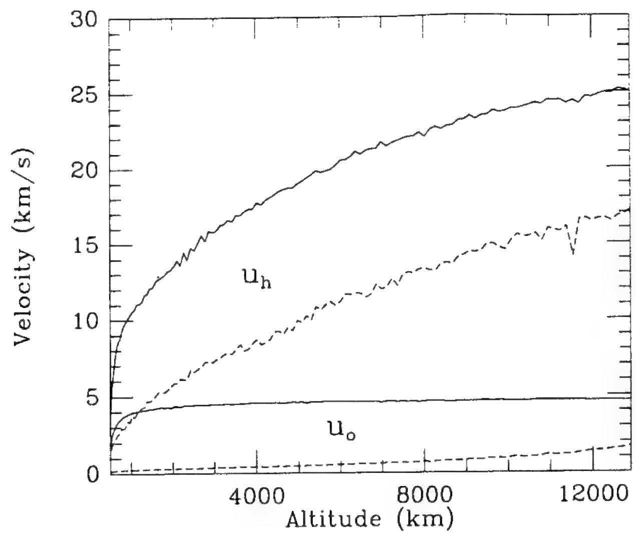

Figure III.4.5: Profiles of ion outflow velocities in the dayside (solid) and nightside (dashed) polar wind solutions.

pact on the ion outflow velocities. The O^+ and H^+ velocities in our two polar wind solutions are shown in Fig. III.4.5. It is clear that both ion species have considerably smaller outflow velocities in the nightside results, in agreement with the observed day-night asymmetry in ion velocities [*Abe et al.*, 1993b].

The absence of photoelectrons in our nightside calculations also leads to the absence of a noticeable electron anisotropy, in contrast to the dayside situation. The parallel temperatures for the upward- and downward-moving electron populations in both of our polar outflow solutions are shown in Fig. III.4.6. The dayside solution reveals a temperature anisotropy between the upwardly and downwardly moving electrons, *i.e.* $T_{e,up} > T_{e,down}$ (the $\|$ subscript is omitted for simplicity). This anisotropy is entirely due to the photoelectrons. In the night-time solution, the temperatures for the two electron populations only differ by about 0.2% at the altitudes where the satellite measurements were made (900 – 1700 km) [*Abe et al.*, 1996]. The dayside and nightside electron temperatures together thus demonstrate the consistency between our photoelectron scenario and the day-night asymmetry observed by the Akebono

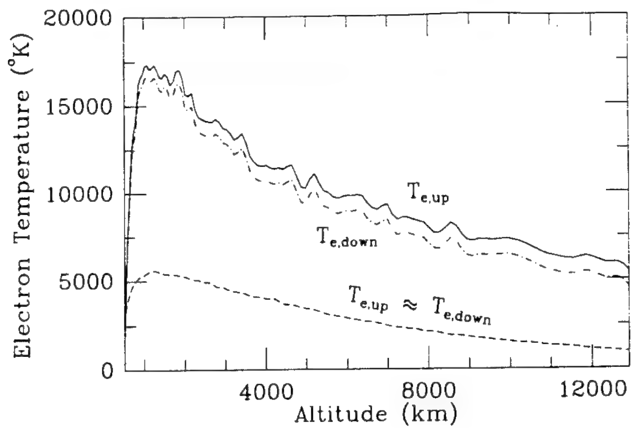

Figure III.4.6: Parallel temperatures for upwardly and downwardly moving electrons, the || subscript has been omitted for simplicity. The dayside temperatures are represented by the solid and dot-dashed lines; the nightside temperatures, which are virtually equal for the two electron populations, are represented by the dashed line.

satellite [*Yau et al.*, 1995; *Abe et al.*, 1996]. Because such a temperature anisotropy was observed in the dayside polar wind [*Yau et al.*, 1995] but seems absent on the nightside [*Abe et al.*, 1996], the role of photoelectrons in our model is consistent with the observed polar wind scenario.

III.4.4 Conclusion

Our work on the polar wind is motivated by the increasing experimental evidence that photoelectrons may affect the dynamics of the polar wind. In particular, the day-night asymmetry in the ion and electron features suggests that photoelectrons may be *the* dominant effects in the polar outflow.

In order to study the impact of photoelectrons on the polar wind, we rely on a self-consistent hybrid model that provides a global kinetic collisional description for the polar wind photoelectrons. The model is hybrid in that it consists of a fluid part for the thermal electrons and a kinetic collisional part, and should be distinguished from other hybrid schemes where, for example, the electrons are treated as a massless

neutralizing fluid. Specifically, in this model, photoelectrons (which are treated as test particles because of their low relative density), and all the ion species (H^+, O^+) are described by a global kinetic collisional approach, while thermal electron properties and the ambipolar electric field are determined by a fluid calculation.

In order to examine the anisotropic kinetic effects of photoelectrons as a source of the day-night asymmetry in the polar outflow, we have generated two polar wind solutions, one corresponding to the daytime outflow, and the other for the nightside. By comparing our dayside and nightside results, we have demonstrated the consistency between our photoelectron scenario and the observations. In particular, we have shown that the presence (absence) of photoelectrons on the dayside (nightside) may explain the observed day-night asymmetry in the polar outflow. For example, the anisotropy between the upward- and downward-moving electrons, which is observed in the sunlit polar outflow but seems absent on the nightside, only appears in our dayside polar outflow results. We have also shown that the presence of photoelectrons leads to a considerably larger self-consistent ambipolar electric field, which corresponds to a larger electric potential difference along the magnetic field line. The magnitude of the ambipolar electric potential has a significant impact on the ion outflow velocities. Thus, both the H^+ and O^+ velocities in our results are remarkably higher on the dayside, in agreement with satellite measurements.

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BOOKS

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- Chandrasekhar Memorial Volume, Special Issue of the International Journal of Engineering Science, Edited by T. Chang and A. C. Eringen, Elsevier, Netherlands, 1998.
- "Physics of Space Plasmas: Multi-Scale Phenomena in Space Plasmas II," Volume 15, edited by Tom Chang and J. R. Jasperse, (MIT Center for Theoretical Geo/Cosmo Plasma Physics, Cambridge, MA 1998).
- "Physics of Space Plasmas: Multi-Scale Phenomena in Space Plasmas," Volume 14, edited by Tom Chang and J. R. Jasperse, (Scientific Publishers, Inc., Cambridge, MA 1996).
- "Physics of Space Plasmas: Chaos, Stochasticity, and Strong Turbulence," Volume 13, edited by Tom Chang and J. R. Jasperse, (Scientific Publishers, Inc., Cambridge, MA 1995).
- "Space Plasmas: Coupling between Small and Medium Scale Processes," AGU Geographical Monograph No. 86, edited by M. Ashour-Abdalla, Tom Chang, and P. Dusenbery, (American Geophysical Union, Washington, D.C., 1995).
- "Physics of Space Plasmas: Controversial Issues and New Frontier Research in Geoplasmas," Volume 12, edited by Tom Chang and J. R. Jasperse, (Scientific Publishers, Inc., Cambridge, MA 1993).

V. INVITED LECTURES

During the grant period, we delivered a total of fifty six (56) invited and review lectures at various national and international conferences and research institutions on topics related to: particle acceleration mechanisms in space, auroral phenomena, self-organized criticality, magnetic substorms, chaos and stochasticity, renormalization group, magnetic reconnection, and the polar wind.

- American Physical Society Plasma Physics Mini-Symposium on Self-Organized Criticality and Turbulence, Seattle, WA, November 1999.
- Goddard Space Flight Center, Series of Invited Tutorial Lectures on Forced and/or Self-Organized Criticality, Greenbelt, MD, October 1999.
- International Topical Conference on Plasma Physics: New Frontiers of Nonlinear Sciences, Trieste, Italy, September 1999.
- Kivelson Symposium, UCLA, Westwood, CA, September 1999.
- Akebono Workshop on Auroral Plasma Dynamics: Akebono Ten Years Later, Banff, Canada, August 1999.
- International Space Science Institute, Special Lecture on Self-Organized Criticality, Bern, Switzerland, August 1999.
- IAGA Symposium on Turbulence and Solitary Structures in Space Plasmas: Theory, Experiments and Data Analyses, Birmingham, England, July 1999.
- AGU Spring Meeting, Special Session on Self-Organized Criticality in Space Plasma Processes, Boston, MA, May 1999.
- Self-Organized Criticality in Space Plasmas, Princeton Plasma Physics Laboratory, NJ, May 1999.
- Imerial College, Tutorials on Self-Organized Criticality, London, England, April 1999.
- URSI National Radio Science Meeting, Commission H Session on the Rale of Self-Organized Criticality in Auroral Plasma Processes, Boulder, Co, January 1999.
- AGU Fall Meeting, Special Session on Nonlinear Methods in Space Plasma Analyses, San Francisco, CA, December 1998.

- Huntsville Workshop: The New Millenium Magnetosphere, Guntersville, AL, October 1998.
- AGU Western Pacific Geophysics Meeting, Taipei, Taiwan, July 1998.
- AGU Chapman Conference on Helicity, Boulder, July 1998.
- Cambridge Workshop on Space Plasmas, Cascais, Portugal, June 1998 (2 lectures).
- VII International Plasma Astrophysics and Space Physics Conference, Lindau, Germany, May 1998.
- Fourth International Conference on Substorms, Nagoya, Japan, April 1998.
- US-Japan Workshop on Magnetic Reconnection, Princeton, NJ, January 1998.
- URSI National Radio Science Meeting, Session on Plasma Waves and Wave-Particle Interactions in Auroral Regions, Boulder, Co, January 1998.
- IPELS '97 Workshop on Current Topics Related to Experiments in Laboratory and Space Plasmas, Maui, Hawaii, June 1997.
- International School on Space Simulations, Kyoto, Japan, March 1997.
- Chapman Conference on the Magnetotail: New Perspectives, Kanazawa, Japan, November 1996.
- Huntsville Workshop: Encounter between Global Observations and Models in the ISTP Era, Guntersville, AL, September 1996.
- General Assembly of the International Union on Radio Science, Lille, France, August 1996.
- Western Pacific Geophysics Meeting, Brisbane, Australia, July 1996.
- Collective Processes in Nonlinear Media, Trieste, Italy, October 1995.
- Harvard-Smithonian Center for Astrophysics, Cambridge, MA, May 1995.
- Workshop/Symposium on Multiscale Phenomena in Space Plasmas, Bermuda, February 1995. (2 lectures.)
- International Symposium on Space Sciences, Taiwan, November 1994.
- Workshop on Coupling of Micro- and Mesoscale Processes in Space Plasma Transport, Guntersville, AL, October 1994. (2 lectures.)
- Western Pacific Geophysics Meeting, Hong Kong, July 1994. (2 lectures.)

- International Conference on Nonlinear Waves and Chaos in Space Plasmas, Kyoto, Japan, June 1994.
- Second International Conference on Magnetic Substorms, Fairbanks, Alaska, March 1994.
- Fall Meeting of the American Geophysical Union, San Francisco, CA, December 1993. (2 lectures.)
- International Conference on Research Trends in Plasma Astrophysics, La Jolla, CA, November 1993.
- Royal Institute of Technology, Stockholm, Sweden, October 1993.
- Swedish Space Research Institute, Kiruna, Sweden, September 1993.
- Swedish Space Research Institute, Uppsala, Sweden, September 1993.
- Swedish Space Research Institute and the University of Umeå, Umeå, Sweden, September 1993.
- International Beacon Satellite Symposium, Cambridge, MA, July 1993.
- International School on Space Plasmas, Volga River, Russia, June 1993. (2 lectures.)
- Space Research Institute, Moscow, Russia, June 1993.
- Second International Workshop on the Interrelationship Between Plasma Experiments in the Laboratory and in Space, Banff, Canada, June 1993.
- Spring Meeting of the American Geophysical Union, Baltimore, MD, May 1993.
- IEEE International Workshop on Plasma Cosmology and Astrophysics, Princeton, N.J., May 1993.
- Space Sciences Laboratory, University of California, Berkeley, CA, April 1993.
- STAR Laboratory, Stanford University, Palo Alto, CA, April 1993.
- Yosemite Meeting on Solar Systems, Yosemite, CA, February 1993.
- Space Science Center, University of New Hampshire, Durham, N.H., February 1993.

VI. SCIENTISTS AND STUDENTS AFFILIATED WITH THE CENTER DURING THE GRANT PERIODS

Tom T.S. Chang, Director

John Belcher, Professor

Stanislaw Olbert, Professor

Hannes Alfvén* (Nobel Laureate), Sponsor of Alfvén Lectureship

W.Y. Tam, Research Scientist

D. Tetreault, Research Scientist

Fareed Yasseen, Research Scientist and affiliate

G.B. Crew, Research Scientist

Jay R. Johnson, Postdoctoral Associate

J.R. Jasperse, Research Affiliate

J.M. Retterer, Research Affiliate

James Ernstmeyer, Graduate Student

C.T. Dum, Research Affiliate

M. André, Visiting Scientist

Andrew Yau, Visiting Scientist

Sandra Chapman, Visiting Scientist

Nick Watkins, Visiting Scientist

J.D. Winningham, Visiting Scientist

Kimani Stencil, Summer Minority Student Awardee

Janel Cobb, Summer Minority Student Awardee

Desiré Miessen, Summer Minority Student Awardee

Vincenzo Vitelli, Visiting Student from Imperial College

Elese Archibald, Visiting Student from Imperial College

Yon Han Lee, Visiting Student from Imperial College

Juan Rodriguez, Visiting Graduate Student from Stanford

Iosif Bena, Undergraduate Research Opportunities Program Awardee

Toma Miloushev, Research Science Institute High School Intern

Wang Fei Cheang, Research Science Institute High School Intern

*Deceased.

BIOGRAPHICAL SKETCHES

Dr. Tom Chang is internationally known for his contributions in charged particle acceleration processes in the Earth's ionosphere and magnetosphere. He is currently directing a Center of Excellence effort in Theoretical Geoplasma Research at the Massachusetts Institute of Technology. In addition to his two Ph.D.'s in theoretical physics and engineering, he has done postdoctoral work at the University of Cambridge in England and was an Honorary Research Fellow at Harvard University's Lyman Laboratory of Physics. He is a Fellow of the American Physical Society and has served for many years as Editor of the international journal, Plasma Physics. He

was the President of the Society of Engineering Science and a member of the NASA Space Physics Theory Working Group (SPTWG) and served as a member of the program committee of the Plasma Physics Division of the American Physical Society and the Committee for Visitors for the NSF Magnetospheric Physics Program. He is the Editor-in-Chief of the popularly referenced AGU monograph, "Ion Acceleration Processes in the Magnetosphere and Ionosphere", a Co-Editor of the recently published AGU monograph, "Space Plasmas: Coupling between Small and Medium Scale Processes", the series Editor of the SPI Conference Proceedings series, "Physics of Space Plasmas", an Associate Editor of the AGU journal, "Review of Geophysics", a Correspondent for the International Journal, "Comments on Plasma Physics and Controlled Fusion", and served as a member of the Steering Committee of the International Conference on Plasma Science. He is the organizer of over a dozen National and International Conferences including the well-established Cambridge Workshop series in Theoretical Geoplasma Physics, which is held at MIT annually each summer, and the recent Chapman Conference on Micro/Meso Scale Phenomena in Space Plasmas. Tom Chang is an author/editor of over 120 scientific publications including 12 books and proceedings volumes. He was the recipient of the prestigious National Thompson Award.

Dr. John Belcher graduated summa cum laude in physics and mathematics from Rice University and obtained his Ph.D. in Physics from the California Institute of Technology. He is internationally known for his innovative theory of Alfvén wave heating of the solar wind and is the principal investigator of the plasma experiment of the Voyager program. He is an authority in the physics of the ionospheres and magnetospheres of all planets and the heliosphere. As Professor of Physics at MIT, Dr. Belcher provides the broad perspective and insight that the Center relies upon in geoplasma research and studies.

Dr. Stanislaw Olbert has a Ph.D. from MIT and was a student of the world-renowned space physicist, Professor Bruno Rossi. He has been interested in the Physics of Space Plasmas since the very beginning. He is the author of the well-known text, "Introduction to the Physics of Space". He is known for his innovative research in cosmic rays, anomalous heat flux in the solar wind, and induced radiative losses of conducting objects in magnetized plasmas. Several of his students, including Dr. George Sciscoe of UCLA (now at Boston University) and Dr. V. Vasyliunas of the Max-Planck Institute for Aeronomy, are now leading authorities in the field of physics of space plasmas. Though retired, Professor Olbert continues to interact with the Center Personnel, particularly in the areas of global kinetic theories of the polar and solar winds.

Professor Hannes Alfvén is the sponsor of the Alfvén Lecture series at MIT. Professor Alfvén is a Nobel Laureate in Space Physics and is known for the Alfvén waves that bear his name. He is generally considered as the father of theoretical space plasma physics. Every year, a world-renowned space physicist is invited to MIT to deliver a plenary lecture (the Alfvén Lecture) and to interact with members of the MIT Center on research topics of mutual interest. Awardees of the lectureship included such luminaries as Professor James van Allen of the University of Iowa (discoverer of the van Allen belt), Professor Jim Dungey of the Imperial College of London (discoverer of the reconnection model of the open magnetosphere), Professor Oscar Buneman of the Stanford University (co-discoverer of the Farley-Buneman instability in ionospheric plasma physics and the Buneman instability), Professor Eugene N. Parker of the University of Chicago (discoverer of the solar wind theory), Professor Charles Kennel of UCLA and currently Associate Administrator of NASA, and others. Professor Alfvén visited MIT periodically until recently and offered advice and precious encouragement to the theorists at MIT that only a Nobel Laureate

could provide. Unfortunately, Professor Alfvén passed away recently. His spirit will, nevertheless, be with our Center forever.

Dr. W.Y. Tam obtained his B.S. degree in physics from the University of California, Berkeley with highest honors. He has an outstanding record at MIT including a top grade in the physics general examination in 1991. Dr. Tam has accomplished a great deal during his tenure at MIT. One of his outstanding achievements is the discovery of a number of inaccuracies and errors in one of the most popular plasma dispersion codes, that have been used world wide for important space plasma instability calculations. He has since developed a much more efficient and versatile plasma dispersion code capable of treating nearly all conceivable geometries and plasma environments using a small size workstation. He has made ground-breaking advances in the global, kinetic theory of the polar wind and solar wind including wave-particle interactions. He has done outstanding research in the field of forced and/or self-organized criticality and written an innovative paper on the application of the real space renormalization-group on this subject. He is currently a research scientist at the center.

Dr. D. Tetreault is a renowned space plasma theorist with 20 years of research experience. A summa cum laude physics graduate from the University of New Hampshire, Dr. Tetreault received his Ph.D. in nonlinear plasma theory and turbulent reconnection processes from the Massachusetts Institute of Technology under the direction of the renowned physicist, Professor Thomas Dupree. Dr. Tetreault is a member of Phi Beta Kappa and Sigma Xi, and held a National Science Foundation Fellowship during the years 1969-72. He has given numerous invited talks on nonlinear plasma theory involving auroral double layers, ion holes, turbulent reconnection and clump theory. He is an author of over 30 research articles in Physics of Fluids, JGR and other refereed journals.

Dr. Fareed Yasseen obtained his Ph.D. from the Polytechnic Institute in Lausanne, Switzerland and was the student of the world-renowned plasma physicist, Professor E. Weibel. Dr. Yasseen has done outstanding research in theoretical plasma physics related to fusion and space applications. His innovative work of the global analysis of collisional effects on photoelectron distributions in the polar wind has generated a new direction in polar wind research and investigators all over the world are following in his footsteps by emulating his ground-breaking ideas.

Dr. G.B. Crew received his A.B. summa cum laude in Physics and Mathematics from Dartmouth College. He was a National Science Foundation Fellow at MIT where he studied under Professor Bruno Coppi and received his Ph.D. in theoretical plasma physics on collisionless magnetic reconnection processes. His research has been directed toward tractable, analytic formulations of space plasma phenomena including those related to the conical distribution of ionospheric ions in the magnetosphere and the stability of current sheets in the magnetotail in the presence of pre-existing turbulence. Dr. Crew is currently a research scientist at the MIT Center for Space Research working on X-ray and gamma ray imaging satellites. He is an author of over 30 scientific papers.

Dr. Jay Johnson was undoubtedly the top graduate student in theoretical space plasma physics at MIT. He came from the University of Colorado with a straight A+ average, where he worked with the famous plasma physicist, Professor Martin Goldman, as an undergraduate honor student. His grades at MIT were outstanding and ranked number one in the physics general examination in 1989. He was a research associate at the University of Alaska. Returning to MIT as a postdoctoral associate in 1993, Dr. Johnson worked with Dr. Chang on such diverse problems as the "black aurora," the kinetic Alfvén waves, and diffusion in the Earth's magnetopause. He is now a research scientist at the Princeton Plasma Physics Laboratory. He has published

a number of papers in the Geophysical Research Letters, the Journal of Geophysical Research, Annales Geophysicae, and the Physics of Plasmas. He has given a number of presentations including invited talks at various international and US conferences. His presentation on "Auroral Turbulence" at the 1990 Fall Meeting of AGU earned him an **Outstanding Paper Award** of the Solar-Planetary Relationship section of the American Geophysical Union.

Dr. John R. Jasperse is head of theoretical space plasma physics at the Air Force Research Laboratory. A Harvard graduate, he has received many research awards (e.g., the Marcus O'Day and Guenter Loeser Awards) for his innovative research in space plasma physics and is internationally renowned for his work in ionospheric plasma instabilities and collisional processes. He has interacted with the MIT group for a number of years. His joint research activities with members at the MIT Center included the understanding of particle acceleration in space plasmas, theory of turbulence, photoelectron distributions in the ionosphere, and other topics. He has jointly sponsored with Dr. Tom Chang at MIT a number of international conferences and workshops. He is the author of over 60 research publications and books.

Dr. John M. Retterer received his Ph.D. in astronomy with high honors from the University of California at Berkeley. He has enjoyed an appointment as Visiting Scientist and Research Affiliate at MIT for a number of years while on staff at the Air Force Research Laboratory. He is known for his innovative research in Monte Carlo and particle-in-cell simulations in space plasma physics, particularly in the field of VLF waves and electron beam excited plasma instabilities. He has been invited to deliver review and invited lectures on his specialty all over the world at many prestigious international conferences. He was the recipient of the Bernard Friedman award for applied mathematics while at Berkeley and a Superior Performance Award from the U.S. Government. He is an author of over 30 scientific publications.

Dr. James Ernstmeyer came to MIT with a straight A average and a perfect score on his SAT examinations. He wrote his combined M.S./B.S. thesis on collisionless shock waves under the direction of Dr. Tom Chang. He was an Air Force Captain and served as Program Manager at the Rome Air Development Center in charge of electron beam generated VLF waves in the ionosphere. He returned to MIT and completed his Ph.D. program in theoretical geoplasma research last year. The topic of his thesis was on the theoretical understanding of upward lightning strokes in the atmosphere/ionosphere.

Dr. C.T. Dum is world-renowned for his work on plasma diffusion theory, mesoscale plasma physics and large scale numerical plasma simulations. Since obtaining his doctoral degree in Physics from MIT, Dr. Dum taught for a few years at the Cornell University before assuming his present position as head of the theory group of the Max-Planck Institute for Extraterrestrial Physics in Garching bei Munchen, Germany. Dr. Dum visits our Center three or four times a year staying for one or two months during each visit. He is a member of the American Physical Society, the American Geophysical Union, and Sigma Xi. He has written over 40 definitive research articles in refereed journals and given over 50 invited and review lectures at many international conferences and workshops.

Dr. Mats André is currently a Principal Professor of Physics at the Uppsala University in Sweden. He was the coordinator for the Swedish Satellite, Freja. Trained as a theoretical space plasma physicist, Dr. Andre has also been deeply involved with the hardware design and data analyses of the Viking and Freja satellites. Dr. Andre is one of Principal Investigators of the recently launched satellites called CLUSTER. Dr. Andre has been collaborating with the MIT Center since its inception and has contributed in the areas of ion heating, electron conics, low frequency turbulence, and double layers.

Dr. Andrew Yau is world-renowned for his contributions to the development of advanced scientific instruments aimed at measuring particle distributions in space and in detecting novel ion conic distributions in the Earth's ionosphere and magnetosphere. He spent six months with us after the AKEBONO satellite was launched. His interactions with the MIT Center led to the development of the photoelectron-driven polar wind theory that was described in this report. He was previously associated with the National Research Council in Canada and now a Professor of Physics at the University of Calgary.

Dr. Sandra Chapman is currently Professor and Head of the Astrophysics Group at the University of Warwick in England. A specialist in Hamiltonian chaos and self-organized criticality, she received the Zeldovich Medal from COSPAR a few years back. She spent several periods with us to do joint research in the area of real-space renormalization-group and its application to forced and/or self-organized systems and substorms.

Dr. Nick Watkins is a senior scientist at the British Antarctic Survey in Cambridge, England. Dr. Watkins was trained in condensed matter physics and became interested in space plasma research recently. He has excelled in the design of correlation instruments in space. He spent a couple of periods with us doing joint research in the field of self-organized criticality and substorms.

Dr. J. D. Winningham is an Institute Scientist at the Southwest Research Institute. He has made numerous seminal contributions to the anomalous particle distributions in the ionosphere and magnetosphere. He was a principal investigator on the Dynamics Explorer satellites and is involved with a number of international space programs. His initial observations of the polar wind electrons and central plasma sheet ions stimulated much of the theoretical work in these areas at the MIT Center.

Mr. Kimani Stencil was a Minority Summer Research Student recruited from the

University of Maryland. Mr. Stencil was in the Honors Program in Physics at the University of Maryland. He was previously a summer intern at the Bell Laboratory and was highly recommended to us by his advisors there. He worked with us on the theory of chaos using the Hamiltonian formulation. He is now an advanced graduate student of the Department of Physics at MIT.

Ms. Janel Cobb was a Summer Intern at our center under the MIT Minority Opportunity Program. Before joining us, she was a summer intern at the National Center for Atmospheric Research in Boulder, CO. She was selected at the Grambling State University for the High Ability Program and a member of the Earl Lester Cole Honors College. She was the recipient of the National Delta Sigma Theta Sorority Scholarship Award and the National Society of Black Physicists Award from the Lawrence Livermore National Laboratory. She worked with us in studying the phenomena of charged particle acceleration in space.

Mr. Desiré Miessen is a Summer Intern under the MIT Minority Opportunity Program. Mr. Miessen has accumulated an outstanding undergraduate record at the City University of New York and obtained high grades in every one of the mathematics courses that he has taken. He has advanced training in high speed computing and is conversant with the modern theories of physics. As an undergraduate student, he is already a teaching assistant in Calculus. Mr. Miessen is working on a frontier research problem on particle acceleration in the ionosphere.

Mr. Vincenzo Vitelli was a top-ranked undergraduate physics student from the Imperial College. He was selected by Professor Dimitri Vvedensky of the Blackett Laboratory to spend one semester at our Center. During his tenure at MIT, Mr. Vitelli participated in the activities of our daily study group learning the tools that are relevant to the stochastic behavior of dynamic systems near criticality related to the space and astrophysical environment. Mr. Vitelli is very intelligent and has the

maturity of a second year graduate student. He learned many of the intricate details of the difficult subject on the dynamic renormalization-group in a short period of only three months. He is now a physics graduate student at the Harvard University.

Ms. Elese Archibald is a brilliant physics student from the Imperial College of London. She was selected by Professor Dimitri Vvedensky of the Blackett Laboratory to spend her summers at the MIT Center. In three short years, she has mastered the research areas of general relativity, cosmology, plasma physics and wave-particle interactions. She is presently undertaking a large scale plasma simulation problem in astrophysics physics. She is now a graduate student in the astronomy department at the University of Edingburgh.

Mr. Yon Han Lee was an outstanding undergraduate physics student from the Imperial College of London. He was selected by Professor Dimitri Vvedensky of the Blackett Laboratory to be a Summer Intern at our Center. He participated in the study of the modern theories of statistical mechanics related the phenomenon of intermittent turbulence in space. During his tenure, he acquired almost all the current concepts of chaos and stochasticity as well as the elements of the theory of the renormalization-group. After completing his studies at Imperial, he became a graduate student of physics at the Columbia University.

Dr. Juan Rodriguez was an advanced graduate student of Professor Umran Inan of the STAR Laboratory at Stanford. He spent the last year of his graduate years at our center while completing his thesis at Stanford. His doctoral dissertation dealt with the propagation of VLF waves in the Earth's ionosphere and magnetosphere. Dr. Rodriguez joined the Air Force Research Laboratory upon obtaining his Ph.D.

Mr. Iosif Bena is an outstanding undergraduate student in physics at MIT. He completed his entire undergraduate program during his freshman year and took a full load of graduate courses during his sophomore year. He has done mode conversion

and ray tracing studies involving the propagation of electromagnetic waves in the magnetosphere/ionosphere. He was an awardee of the MIT Undergraduate Research Opportunities Program (UROP).

Mr. Toma Miloushev was recruited (through the worldwide talent search) by the Center for Excellence in Education as one of our Summer Intern for the Research Science Institute. He came from an outstanding high school in Bulgaria and was their top ranking student. He is extremely talented and knows over ten languages. As a Junior student in high school, he already mastered most of the mathematical and physical theories at the college level. At MIT, he formulated an interesting theory of wave particle acceleration in the Earth's magnetosphere and ionosphere and solved the problem analytically with advanced mathematical techniques.

Mr. Wang Fei Cheang was recruited (through the worldwide talent search) by the Center for Excellence in Education as one of our Summer Intern for the Research Science Institute. He came from an outstanding high school in Macao and was their top ranking student. Mr. Cheang is extremely bright and quick with physical and mathematical concepts. During his tenure (as a Junior in high school), he quickly acquired the basic knowledge of calculus, differential equations, vector analysis and the theory of electricity and magnetism. He did outstanding research during his tenure in charged particle acceleration in space and excelled in solving the research problem using the technique of Monte Carlo simulations.